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Green Hydrogen: the Holy Grail of Decarbonisation? An Analysis of the Technical and Geopolitical Implications of the Future Hydrogen Economy

Rossana Scita, Pier Paolo Raimondi and Michel Noussan

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By Rossana Scita, Fondazione Eni Enrico Mattei
Pier Paolo Raimondi, Fondazione Eni Enrico Mattei
Michel Noussan, Fondazione Eni Enrico Mattei

Summary

Hydrogen is currently enjoying a renewed and widespread momentum in the energy market. In the last years, demand for hydrogen has substantially increased worldwide, with several countries developing hydrogen national strategies, and private companies investing in the development of hydrogen related projects. Green hydrogen's environmental sustainability and versatility contribute to its representation as the holy grail of decarbonisation. This working paper challenges this definition, by analysing the historical process which contributed to hydrogen's rise, showing the current uses of hydrogen and the major obstacles to the implementation of a green hydrogen economy, and assessing the geopolitical implications of a future hydrogen society. Particularly, the paper shows that the hydrogen economy is still far from becoming reality. Even though investments in green hydrogen technologies and projects have increased over the last decade, there still remains a high number of unresolved issues, relating to technical challenges and geopolitical implications. Nonetheless, a clean hydrogen economy offers promising opportunities not only to fight climate change, but also to redraw geopolitical relations between states. The energy transition is already taking place, with renewable energies gradually eroding the global energy system based on fossil fuels. A global transformation, set in motion by the need to decarbonise the energy system, will have the potential to redraw international alliances and conflicts. In this context, hydrogen may play a crucial role. By 2050, hydrogen could indeed meet up to 24% of the world's energy needs, thus highly influencing the geopolitical landscape. In this regard, the choice over which pathway to take for the creation of hydrogen value chains will have a huge geopolitical impact, resulting in new dependencies and rivalries between states. Conclusively, if national governments are willing to spur the emergence of a green hydrogen economy, they should heavily invest in research and development, encourage the development of a clean hydrogen value chain, and promote common international standards. Moreover, they should also take into account hydrogen's geopolitical implications. If the hydrogen economy is well-managed, it could indeed increase energy security, diversify the economy, and strengthen partnerships with third countries.

Keywords: Green Hydrogen, Decarbonization, Energy, Energy Policy

JEL Classification: Q4, Q42, O14

Address for correspondence:
Rossana Scita
Fondazione Eni Enrico Mattei
C.so Magenta, 63
20123 Milan
Italy
Email: rossana.scita@gmail.com

Green Hydrogen: the Holy Grail of Decarbonisation?

An analysis of the technical and geopolitical implications of the future hydrogen economy

Rossana ***Scita****, *Pier Paolo* ***Raimondi*** *and Michel* ***Noussan***

Fondazione Eni Enrico Mattei, Milan

** corresponding author, rossana.scita@gmail.com*

Abstract

Hydrogen is currently enjoying a renewed and widespread momentum in the energy market. In the last years, demand for hydrogen has substantially increased worldwide, with several countries developing hydrogen national strategies, and private companies investing in the development of hydrogen related projects. Green hydrogen's environmental sustainability and versatility contribute to its representation as the holy grail of decarbonisation.

This working paper challenges this definition, by analysing the historical process which contributed to hydrogen's rise, showing the current uses of hydrogen and the major obstacles to the implementation of a green hydrogen economy, and assessing the geopolitical implications of a future hydrogen society. Particularly, the paper shows that the hydrogen economy is still far from becoming reality. Even though investments in green hydrogen technologies and projects have increased over the last decade, there still remains a high number of unresolved issues, relating to technical challenges and geopolitical implications.

Nonetheless, a clean hydrogen economy offers promising opportunities not only to fight climate change, but also to redraw geopolitical relations between states. The energy transition is already taking place, with renewable energies gradually eroding the global energy system based on fossil fuels. A global transformation, set in motion by the need to decarbonise the energy system, will have the potential to redraw international alliances and conflicts. In this context, hydrogen may play a crucial role. By 2050, hydrogen could indeed meet up to 24% of the world's energy needs, thus highly influencing the geopolitical landscape. In this regard, the choice over which pathway to take for the creation of hydrogen value chains will have a huge geopolitical impact, resulting in new dependencies and rivalries between states.

Conclusively, if national governments are willing to spur the emergence of a green hydrogen economy, they should heavily invest in research and development, encourage the development of a clean hydrogen value chain, and promote common international standards. Moreover, they should also take into account hydrogen's geopolitical implications. If the hydrogen economy is well-managed, it could indeed increase energy security, diversify the economy, and strengthen partnerships with third countries.

Contents

1. Introduction

Hydrogen is currently enjoying a renewed and widespread momentum in the energy market. As concerns about climate change are increasing, governments are looking at hydrogen as a possible solution to reach carbon neutrality goals. The global effort to limit global warming to less than 2°C, set in the 2015 Paris Agreement, might thus pave the way to the use of hydrogen as an important component of the future energy mix.
Indeed, hydrogen is a sustainable and versatile energy carrier. Sustainable because it does not directly emit greenhouse gases or air pollutants, and versatile because it can be used in a wide range of applications, from the transport to the industry, power and building sectors. Thus, renewable hydrogen – produced by electrolysis using renewable electricity - could play a pivotal role in the transition to a low-carbon economy, replacing carbon-rich fuels in "hard-to-abate" sectors.

In the last years, demand for hydrogen has substantially increased worldwide, with several countries developing hydrogen national strategies[1], and private companies investing in the development of hydrogen related projects. As highlighted by the International Energy Agency in its 2019 report[2], global spending on hydrogen energy research, development and demonstration has increased over the past few years, leading to political and business momentum.
That being said, political interest in hydrogen is not new. Over the past five decades, there have been several waves of enthusiasm for hydrogen's potential. Particularly since the 1970s oil crisis, experts have started to look at hydrogen as a possible key player in the energy market, able to increase energy security and address air pollution issues. Nonetheless, after initial peaks of interest, hydrogen did not replace fossil fuels, resulting in disillusionment.
Thus, it remains to be seen if this time will be different. According to the predominant viewpoint, the energy landscape has changed enough to pave the way to the rise of a hydrogen economy, able to break the hegemony of fossil fuels and mitigate the shortcomings of renewable energy sources.
However, the mainstream has often overlooked a high number of unresolved issues, which might hinder the full implementation of a hydrogen economy, namely elevated costs of production, high investment risk, and the lack of existing infrastructures. All these problems should be first overcome, in order to develop a global hydrogen market.

Moreover, a hydrogen economy would have long-lasting consequences on the geopolitical status-quo, reshaping the energy geopolitics. The energy transition is already taking place, with renewable energies gradually eroding the global energy system based on fossil fuels. A global transformation, set in motion by the need to decarbonise the energy system, will have the potential to redraw international alliances and conflicts. In this context, hydrogen may play a crucial role.
Thanks to its characteristics, hydrogen can be stored for a long period of time, balancing the fluctuations in renewable generation. By 2050 hydrogen could meet up to 24% of the world's energy needs[3], thus highly impacting the geopolitical landscape. In this regard, the choice over which pathway to take for the creation of hydrogen value chains will have a huge geopolitical impact, resulting in new dependencies and rivalries between states.

The aim of this paper is to provide a comprehensive analysis of a future clean hydrogen economy, through the assessment of the current opportunities and obstacles to its full implementation. The

[1] See the table attached: Hydrogen main Strategies / Projects Worldwide
[2] IEA (2019), "*The Future of Hydrogen: seizing today's opportunities*"
[3] Bloomberg New Energy Finance (2020), "*Hydrogen Economy Outlook*"

paper will firstly offer an overview of the previous waves of enthusiasm for hydrogen, secondly it will analyse the main obstacles to overcome for the development of a clean hydrogen economy, and finally it will assess the geopolitical implications of a future hydrogen economy.

Types of Hydrogen:

Hydrogen can be produced through a variety processes, all of which have a different climate impact. In order to enhance clarity, this paper will use the following definitions:

Green hydrogen: hydrogen produced through the electrolysis of water, with electricity from renewable sources; greenhouse gas emissions close to zero.

Yellow hydrogen: hydrogen produced through the electrolysis of water, using nuclear electricity; greenhouse gas emissions close to zero.

Blue hydrogen: hydrogen produced through steam methane reforming with carbon capture and storage (CCS); low levels of greenhouse gas emissions.

Turquoise hydrogen: hydrogen produced through pyrolysis with carbon black as a by-product; low levels of greenhouse gas emissions

Grey hydrogen: hydrogen produced through steam methane reforming without CCS, using natural gas; high levels of greenhouse gas emissions.

Renewable hydrogen: synonym for green hydrogen

Clean hydrogen: synonym for green hydrogen

Low-carbon hydrogen: encompasses fossil-based hydrogen with carbon capture and electricity-based hydrogen, with significantly reduced full life-cycle greenhouse gas emissions compared to existing hydrogen production; it includes green, yellow, blue, and turquoise hydrogen.

Box 1: Types of Hydrogen

2. Previous waves of enthusiasm for hydrogen: will this time be different?

"The foundation is already being laid for the hydrogen economy. In the next few years the computer and telecommunications revolution is going to fuse with the new hydrogen-energy revolution, making for a powerful mix that could fundamentally reconfigure human relationships in the 21st and 22nd centuries"[4].

These words might have been pronounced today, with the vast majority of energy market analysts sustaining the emergence of a global hydrogen economy in the next few years.
But these words were actually pronounced 20 years ago, when the famous economist Jeremy Rifkin envisioned a new society, in which hydrogen would have replaced fossil fuels. In the early 2000s interest in hydrogen's potential was high, with various scholars sustaining that this new clean energy solution had reached its final momentum. It did not happen. The hydrogen economy did not take off, and its popularity declined as it had increased.

In the past five decades there have been several waves of popularity for hydrogen, but so far they ended up being false starts.
In the 1970s interest in hydrogen's potential began to grow as a consequence of oil price shocks, petroleum shortages, and environmental awareness - particularly linked to automotive pollution. In 1970, Prof. John Bockris[5] coined for the first time the term "hydrogen economy", during a talk at the General Motors Technical Center. In the same year, Prof. Lawrence W. Jones of the University of Michigan published a technical report entitled "Toward a Liquid Hydrogen Fuel Economy"[6], suggesting "the possibility of using liquid hydrogen as an ultimate replacement of fossil hydrocarbon fuels" (Jones 1970:1). Through the decade, several academics and engineers argued in favour of hydrogen, claiming that hydrogen produced from coal or nuclear electricity would have had the potential to provide a new source of energy, mainly in the transport sector. This enthusiasm led to the making of new projects and associations on hydrogen, including the International Energy Agency Hydrogen and Fuel Cell Technology Collaboration Programme – launched in 1977 -, and the International Journal of Hydrogen Energy - launched in 1976. Nonetheless, as soon as oil prices decreased, gas and oil resources proved abundant, and air pollution was controlled by other measures, the need to find an alternative source of energy waned. Thus, hydrogen was put aside.
In the 1990s and early 2000s a new wave of enthusiasm for hydrogen rose due to increasing concern about climate change. Similarly to the previous wave, the research mainly focused on the transport sector, but this time it was given more importance to the eco-friendly characteristics of hydrogen, with a specific focus on carbon capture and storage. During this period, various nations and companies started to invest in hydrogen, believing in its potential as a sustainable energy option. In 1993, Japan invested JPY 4.5 billion in a long-term programme for international hydrogen trade based on renewable energy. The previous year, in 1992, the EU Commission and the

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[4] Rifkin Jeremy (2002), *"The Hydrogen Economy: The Creation of the Worldwide Energy Web and the Redistribution of Power on Earth"*, Tarcherperigree
[5] Infinite Energy Magazine (2013), *"Dr. O'M. John Bockris 1923–2013"*, Infinite Energy Magazine, Issue 111, http://www.infinite-energy.com/images/pdfs/BockrisObit.pdf
[6] Jones Lawrence (1970), *"Toward a liquid hydrogen fuel economy"*, University of Michigan, https://deepblue.lib.umich.edu/handle/2027.42/5800

Government of Quebec, in partnership with industries and research centres, had funded various hydrogen pilot projects, aimed at exploring the potential of this new energy source in urban transportation and international shipments. In the wake of these investments and thanks to the continuous enhancement of fuel cells, many automakers – including GM, Toyota, and DaimlerChrysler - unveiled plans for the development of hydrogen cars[7]. Even subsequently, in the early 2000s, interest in hydrogen continued to be high, with further investments in hydrogen powered vehicles. In 2003 the United States launched the International Partnership for Hydrogen and Fuel Cells in the Economy, with the aim of fostering international cooperation on hydrogen and fuel cell R&D, common codes and standards, and information sharing on infrastructure development[8]. However, once again, interest in hydrogen ended in disillusionment, largely as a consequence of disappointment in climate policies implementation, high costs of hydrogen infrastructures, and the development of battery electric vehicles.

Nowadays, hydrogen has gained momentum, again. The European Commission has recently released a hydrogen strategy, preceded by Germany, Japan, Australia and other countries with their own hydrogen national strategies – all of them with specific implementation plans for a hydrogen economy. The mainstream research seems to be highly positive on the possibility of developing a hydrogen economy, sustaining that the time is come to invest in a hydrogen global market.

But why should this time be different? Will a hydrogen economy finally bear fruit or will it prove to be a false start once again?

History teaches not to commit the same mistakes of the past; therefore policymakers should not confuse a renewed momentum for hydrogen with the full implementation of a hydrogen economy. Nonetheless, this time might be different from the previous waves of enthusiasm, with hydrogen finally achieving long-lasting momentum. This is the case mainly for three reasons, namely the increasing applications offered by hydrogen, the need to greener the world economy, and the changed geopolitical scenario.

First, the potential uses of hydrogen are nowadays greater than in the previous decades. While previously the research mainly focused on the use of fuel cells in the transport sector, currently it explores a broader range of applications[9]. Indeed, in the small-distance transport sector hydrogen is generally less competitive if compared to electric-powered vehicles. On the contrary, it plays a fundamental role in hard to abate sectors, such as long-distance and heavy transport – including aviation and shipping -, iron and steel production, and chemicals manufacture[10]. Recently, policymakers have focused on clean hydrogen as a leading option in these sectors, where it can replace or at least reduce the use of oil, coal, and natural gas.

Second, popular support for renewable energy has never been so high. Increasing concern about climate change has led millions of people worldwide to ask for immediate action, prompting national governments to look for alternatives to fossil fuels. The 2015 Paris Agreement and the subsequent international Climate Summits showed that strong political action is needed to counter the effects of global warming, pointing out the necessity to reach zero net CO_2 emissions by 2050. In this context, hydrogen has emerged as a viable option to help decarbonise the world economy. Particularly, hydrogen has the capacity to mitigate the shortcomings of renewable energy sources by

[7] Hydrogen Europe, *"Hydrogen Cars"*, https://www.hydrogeneurope.eu/hydrogen-cars
[8] US Department of Energy, Office of Energy Efficiency and Renewable Energy, *"International Partnership for Hydrogen and Fuel Cells in the Economy"*, https://www.energy.gov/eere/fuelcells/international-partnership-hydrogen-and-fuel-cells-economy
[9] Financial Times (2019), *"Hydrogen could help decarbonise the global economy"*, https://www.ft.com/content/959d08e2-a899-11e9-984c-fac8325aaa04
[10] IEA (2019), *"The Future of Hydrogen: seizing today's opportunities"*

storing energy, thus coping with fluctuating wind and solar electricity production[11]. While hydrogen has always been considered a possible solution to reduce carbon emissions, awareness that we are close to a tipping point in the climate system may accelerate the development of a hydrogen economy.

Third, the Covid-19 pandemic has fostered a process of geopolitical transformation, in which new energy sources will play a crucial role. Geopolitical dynamics are already changing, with multilateralism threatened by increasing international competition, and non-state actors gaining power. The Covid-19 pandemic and the resulting economic crisis have accelerated this process of global transformation, which will result in new international dynamics. Specifically, the international order will be led by those states able to recover from the crisis, investing in innovation. In this context, renewable sources will play a central role, gradually breaking the hegemony of fossil fuels – and thus the power of oil rich countries -, and reshaping dependencies between states. Investing in hydrogen may appear as an opportunity to achieve energy independence and develop industrial leadership in an emerging field. As a matter of fact, hydrogen is an integral component of many post Covid-19 national recovery plans[12].

> *"The worldwide hydrogen energy web will be the next great technological, commercial, and social revolution in history. […] The switch to a hydrogen economy can end the world's reliance on imported oil and can help diffuse the dangerous geopolitical game being played out between Muslim militants (in the Middle East and elsewhere) and Western powers. Equally important, weaning the world away from a fossil-fuel energy regime will limit CO_2 emissions to only twice their preindustrial levels and mitigate the effects of global warming on the Earth's already beleaguered biosphere"*[13].

Jeremy Rifkin's vision of the hydrogen economy society certainly contributed to raise enthusiasm towards a future hydrogen economy, representing hydrogen as a possible solution not only to global warming, but also to geopolitical instability. However, he was excessively optimistic.

A hydrogen economy will probably take place, but its extent will certainly be lower than the one envisioned by Prof. Jeremy Rifkin. In the long-term, hydrogen may constitute an integral component of the energy mix, contributing to greener hard to abate sectors and mitigating the shortcoming of renewable energies. Nonetheless, it appears more feasible that hydrogen will fill in the gaps, rather than dominating the economy[14].

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[11] Financial Times (2019), *"How hydrogen can offer a clean energy future"*, https://www.ft.com/content/8d0b818c-81f6-11e9-a7f0-77d3101896ec

[12] See the table attached: Hydrogen main Strategies / Projects Worldwide

[13] Rifkin Jeremy (2002), *"The Hydrogen Economy: The Creation of the Worldwide Energy Web and the Redistribution of Power on Earth"*, Tarcherperigree

[14] The Economist (2020), *"After many false starts, hydrogen power might now bear fruit"*, https://www.economist.com/science-and-technology/2020/07/04/after-many-false-starts-hydrogen-power-might-now-bear-fruit

3. Barriers to the implementation of a clean hydrogen economy

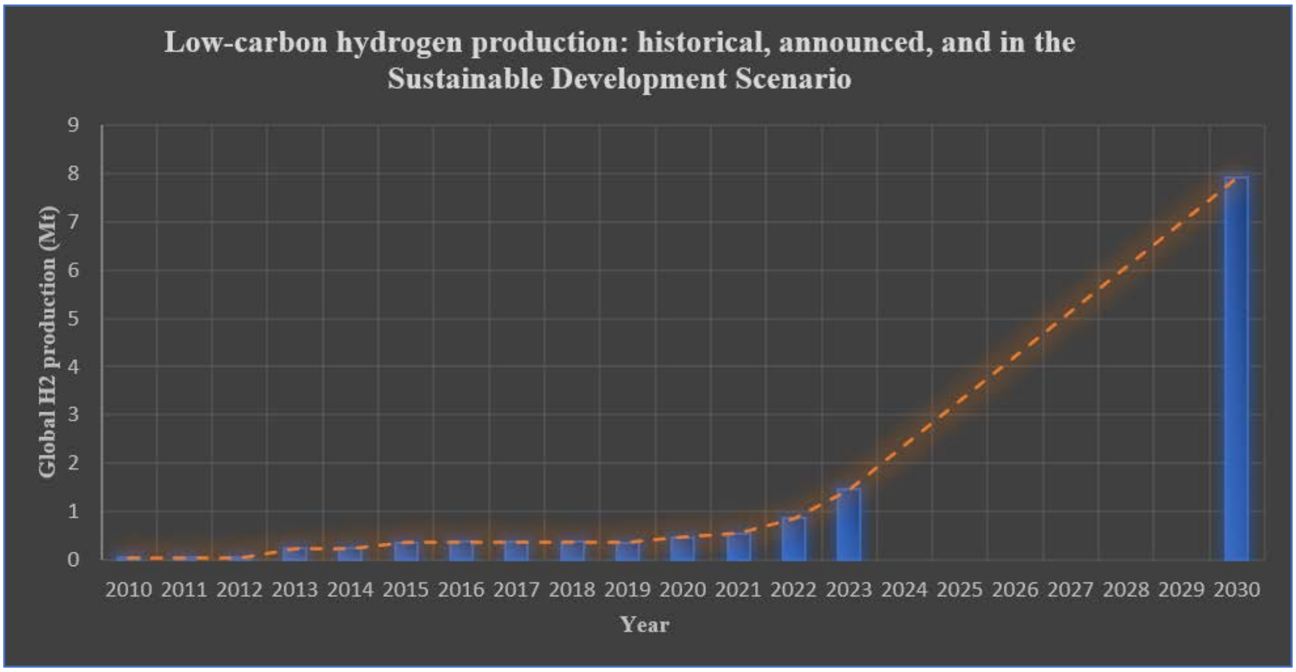
Today, the global production of hydrogen is around 120 million tonnes per year, of which 70 Mt are pure hydrogen and the rest are a mixture with other gases. This data accounts for about 4% of global
final energy and non-energy use, according to the International Energy Agency statistics[15]. Currently, the main applications of hydrogen are in the chemical, metallurgic, and transport sectors, with about 55 % of the worldwide hydrogen production used for ammonia synthesis, 25 % in refineries and about 10 % for methanol production[16].
As shown by IEA statistics[17], over the last decades global annual demand for hydrogen has increased, but 99% of it is still supplied from fossil fuels. Indeed, only 0.7% of current hydrogen production comes from renewable sources or fossil fuel plants with carbon capture and storage, making hydrogen production responsible for around 830Mt of carbon dioxide per year - equivalent to the CO_2 emissions of Indonesia and the United Kingdom combined.

Taking into account these considerations, the major challenge for the development of a clean hydrogen economy remains not only the scaling-up of hydrogen production, but also and mainly the transition from carbon-intensive to low-carbon hydrogen production. Indeed, as shown in the following chart *(Figure 1)*, reaching the low-carbon hydrogen production levels necessary to meet the Sustainable Development Scenario remains an ambitious goal.

Figure 1

Source: Author's elaboration based on data from IEA, *"Low-carbon hydrogen production, 2010-2030, historical, announced and in the Sustainable Development Scenario, 2030"*, https://www.iea.org/data-and-statistics/charts/low-carbon-hydrogen-production-2010-2030-historical-announced-and-in-the-sustainable-development-scenario-2030

[15] IRENA (2019), *"Hydrogen: a Renewable Energy Perspective"*
[16] Hydrogen Europe, *"Hydrogen Applications"*, https://hydrogeneurope.eu/hydrogen-applications
[17] IEA (2019), *"The Future of Hydrogen: seizing today's opportunities"*



Specifically, there are three major obstacles to the implementation of a clean hydrogen economy, namely elevated costs of production, the lack of an existing value chain, and the need for international standards.

3.1 Green Hydrogen's elevated costs

Green hydrogen's high production costs constitute the main barrier to the development of a clean hydrogen global market. In the energy market, hydrogen is indeed subject to market demand preferences and the competition from competing energy sources. Currently, green hydrogen production costs are still too elevated to economically compete with other energy sources or with hydrogen produced from fossil fuels, thus impeding a global clean hydrogen market to develop.

According to an IEA analysis (2019), until 2030, hydrogen production from fossil fuels will remain the most cost-competitive option. Low-carbon hydrogen is indeed much more costly than grey hydrogen:

Hydrogen production costs (2019)[18]

Green hydrogen: $ 2.5-5 a kilogram
Blue hydrogen: $ 1.50-3.50 a kilogram
Grey hydrogen: around $1.50 a kilogram

[18] Source: BloombergNEF (2020)

Moreover, hydrogen is expensive not only to produce, but also to transport, store, and deliver to end users. Hydrogen has indeed a low energy density, which makes it more difficult to store and transport than fossil fuels, thus increasing its costs. For this reason, the research has focused on the possibility of converting hydrogen into hydrogen-based fuels and feedstocks - such as ammonia, synthetic methane, and synthetic liquid fuels - , which are easier to store and transport, and in some cases are directly used in energy applications. This process would reduce delivery costs, thanks to the use of the existing infrastructure. However, many of the technology pathways to produce these hydrogen-based fuels and feedstocks are still not fully operational and can require the use of carbon, resulting in further costs[19] and environmental damages.

In addition to these challenges, hydrogen also encounters efficiency losses, which further contribute to raise its cost, making green hydrogen less competitive than other energy sources. According to the International Energy Agency (2019), "after converting electricity to hydrogen, shipping it and storing it, then converting it back to electricity in a fuel cell, the delivered energy can be below 30% of what was in the initial electricity input"[20]. For this reason, in many cases, it appears more convenient to directly use electricity, instead of converting it into hydrogen and then reconverting it into electricity. For instance, the storage cycle losses of a lithium-ion battery are only around 15%[21]. Of course, hydrogen's energy efficiency also highly depends on its various applications, making it more convenient in certain sectors than others. Taking into account these considerations, reducing energy losses is crucial to reduce hydrogen supply cost.

Conclusively, the final cost of hydrogen depends on all the stages of the supply chain. Specifically, it depends on the infrastructure of exporting and importing countries, the different production pathways, the distances of hydrogen distribution, the mode of transport, and the end-use demand. Technology also plays an important role, potentially impacting on future costs reduction.

Today, clean hydrogen is not yet cost-competitive. Nevertheless, there are encouraging signs that in the near future green hydrogen production costs will decline, paving the way for a global hydrogen market. Plummeting costs of renewable energy and electrolysers, and technological development will indeed contribute to reduce production costs. Over the period 2010 – 2019, costs of solar photovoltaics have declined by 82%, concentrating solar power by 47%, onshore wind by 40%, and offshore wind by 29%[22]. Contemporarily, the costs of electrolysers fell by 60%, and are expected to reduce even further in the next few years[23]. According to BloombergNEF, "renewable hydrogen could be produced for $0.8 to $1.6/kg in most parts of the world before 2050. This is equivalent to gas priced at $6-12/MMBtu, making it competitive with current natural gas prices in Brazil, China, India, Germany and Scandinavia on an energy-equivalent basis, and cheaper than producing hydrogen from natural gas or coal with carbon capture and storage" *(Figure 2)*[24].

Even according to other renewed research centres, green hydrogen costs are expected to dramatically reduce. Particularly, Wood Mackanzie estimates that on average, green hydrogen production costs will equal fossil fuel-based hydrogen by 2040, falling by up to 64%[25]. Given the high hydrogen policy support, 2020 is seen as an inflection point in the trajectory of low-carbon hydrogen, with data showing that whereas blue and grey hydrogen costs will rise, green hydrogen

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[19] For more details on hydrogen-based fuels and feedstocks costs see: IEA (2019), *"The Future of Hydrogen: seizing today's opportunities"*, pp. 55-63

[20] IEA (2019), *"The Future of Hydrogen: seizing today's opportunities"*, p.33

[21] IEA (2019), *"The Future of Hydrogen: seizing today's opportunities"*, p.154

[22] IRENA (2020), *"Renewable Power Generation Costs in 2019"*, International Renewable Energy Agency, Abu Dhabi

[23] Based on cost assessments of IEA, IRENA and BNEF

[24] Bloomberg New Energy Finance (2020), *"Hydrogen Economy Outlook"*, p.2

[25] Wood Mackanzie (2020), *"Green hydrogen costs to fall by up to 64% by 2040"*, https://www.woodmac.com/press-releases/green-hydrogen-costs-to-fall-by-up-to-64-by-2040/

costs will decline[25]. Moreover, currently green hydrogen costs do not reflect externalities, i.e. carbon emissions. In case national governments would put high carbon taxes, this comparison would dramatically change, encouraging the production of green hydrogen.

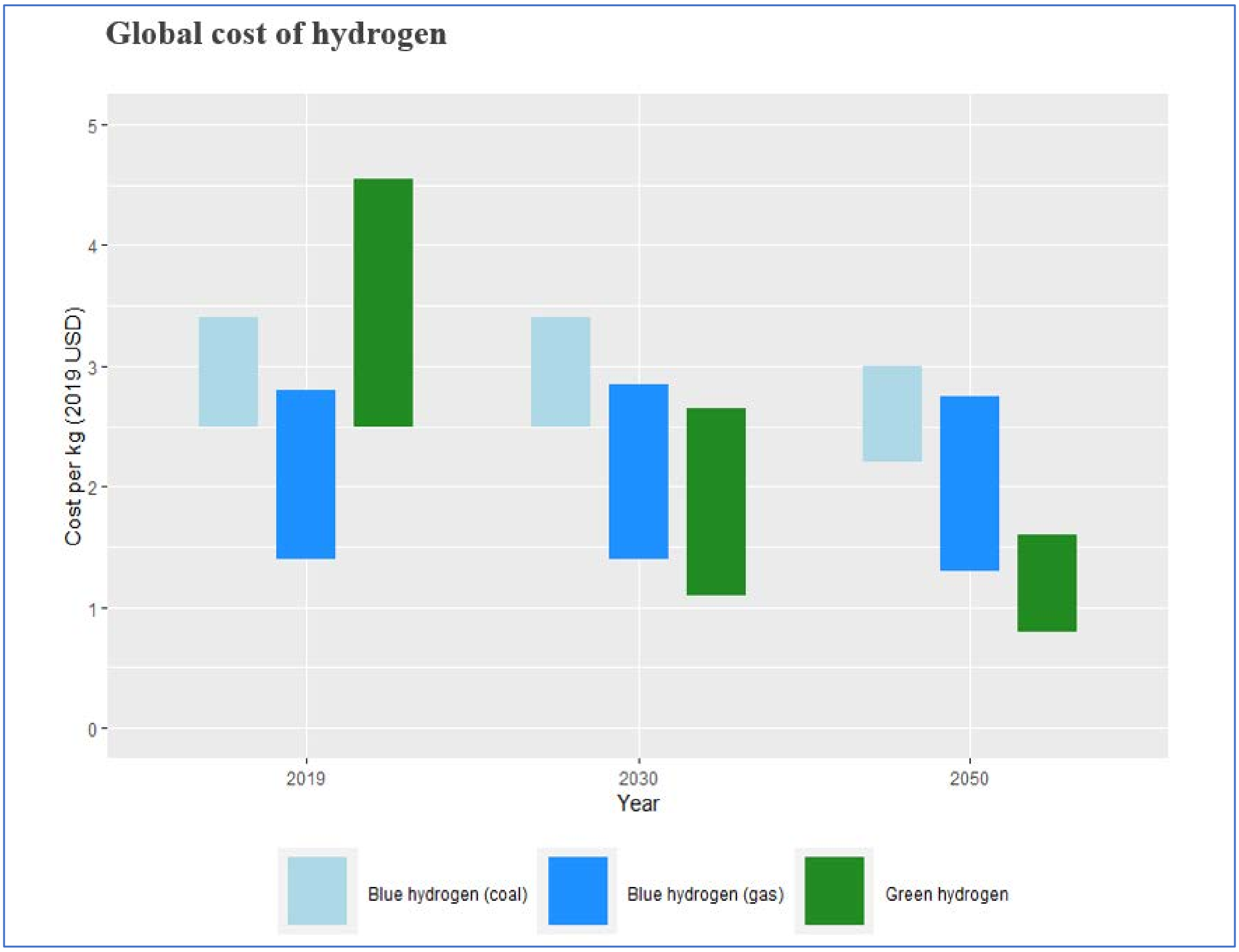

Figure 2

Source: Author's elaboration based on data from BloombergNEF, Bloomberg New Energy Finance (2020), "*Hydrogen Economy Outlook*"
Note: Renewable hydrogen costs based on large projects with optimistic projections for capex. Natural gas prices range from $1.1-10.3/MMBtu, coal from $40-116/t

3.2 Lack of a clean Hydrogen value chain

The lack of an existing clean hydrogen value chain represents one of the major obstacles to overcome for the development of a low-carbon hydrogen economy. Nowadays, hydrogen value chains are indeed mainly dominated by fossil fuels, with only a few pilot projects on low-carbon hydrogen. A global clean hydrogen market would thus require creating completely new value chains. Specifically, the major challenge lies on the choice over which pathway to take, since hydrogen can follow different paths in the supply, handling, and demand chains *(Figure 3)*. Hydrogen can indeed be produced, transported and distributed in different ways, and its demand can come from different sectors. The most competitive outcome will depend on the technologies and infrastructures involved, and it will vary in different regions and applications.

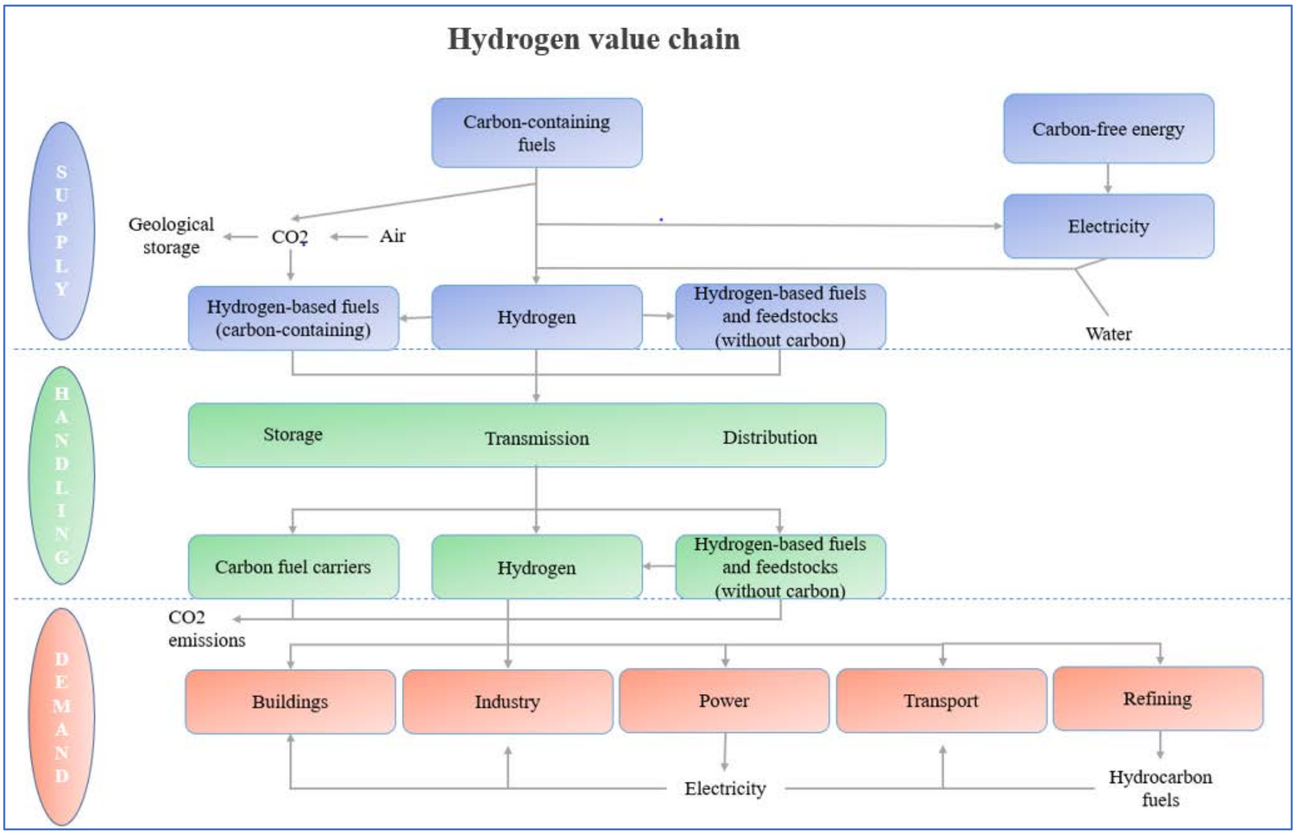

Figure 3

Source: Author's elaboration based on data from IEA (2019), *"The Future of Hydrogen: seizing today's opportunities"*

In terms of production, the main challenge will be to choose between green, blue, or yellow hydrogen[26]. While all these pathways have the same final result, i.e. producing low-carbon hydrogen, they have different implications in terms of infrastructure, industry and, most importantly, environmental impact.

Currently, green and blue hydrogen are the main contenders, especially in Europe. The major difference lies in the fact that while blue hydrogen supports the extraction of natural gas and the CCS industry, green hydrogen encourages renewable energies production. Moreover, green hydrogen, produced through the electrolysis of water, requires higher volumes of freshwater, making its production more difficult in arid regions, such as the Middle East and North Africa. Considering that, due to global warming, clean water availability will be further reduced, these countries should thus invest in desalination capacity. Desalination appears indeed as the best solution in order to enhance green hydrogen's production in an increasingly dry planet, although requiring additional energy consumption in a pathway that is already penalized by a low conversion efficiency.

In the long-term, the best option in terms of climate impact certainly remains green hydrogen, which should remain the final goal. Nonetheless, green hydrogen is still economically non-convenient, due to the high competitiveness of fossil fuels. Thus, blue hydrogen might play a

[26] For more details on green, blue, and yellow hydrogen see: *Figure 1*

crucial role in a transition phase, paving the way for a green hydrogen market[27]. In this regard, it would be fundamental to higher carbon prices, which would allow benefiting from CO_2 handling and sequestration or use, thus attracting oil and gas companies. As the transition to a green economy is subject to investments in clean energy sources, increasing carbon prices appears as the best option, to hamper carbon intensive activities, and stimulate greener options[28].

In regard to yellow hydrogen - obtained through electrolysis or thermochemical processes using nuclear energy - , its production represents an emerging alternative to steam-methane reforming. Yellow hydrogen is often presented as a promising solution, thanks to its low carbon footprint, and various countries are encouraging its production in order to relaunch nuclear power plants. In fact, after the slow decline of nuclear power in the last three decades, yellow hydrogen is seen as a promising option for energy companies with a substantial portfolio of nuclear power plants[29]. For instance, in 2019 the French EDF – a company which owns 58 nuclear reactors - launched Hynamics, a subsidiary company which provides supply and maintenance of electrolysers and hydrogen vehicle fuelling. Moreover, some countries – including the United States[30] - look at hydrogen as a way to save or even boost nuclear – especially China, India, Russia, and the UAE, which are building new power plants or

Taking into account the pros and cons of yellow hydrogen, hydrogen production from nuclear energy may certainly contribute to reduce carbon emissions, while representing an economically convenient option in several countries. However, it should not be forgotten that nuclear energy has serious environmental impacts, including safety concerns, the potential release of radioactive gases and effluents and, last but not least, the production of nuclear waste.

In terms of transport and storage, the main difficulties will be the building of a huge infrastructure and the need for cross-border cooperation. Nowadays, hydrogen is usually produced and consumed on-site, with relatively low costs. Building a global hydrogen market would thus require huge investments in infrastructure development, such as pipeline and delivery networks. Moreover, a well-functioning handling value chain would require a range of technologies, able to store and transport hydrogen in the most effective and cheaper way.

First of all, hydrogen has to be stored, an operation which requires a choice between different paths, each one with their specific advantages and downsides. Currently, hydrogen is usually stored as a gas or liquid in tanks, for small-scale mobile and stationary applications. But large-scale trade would involve a broader variety of options, whose efficiency will depend on "the volume to be stored, the duration of storage, the required speed of discharge, and the geographic availability of different options. In general, however, geological storage is the best option for large-scale and long-term storage, while tanks are more suitable for short-term and small-scale storage"[31].

Secondly, hydrogen has to be transmitted and distributed, an operation that can be very difficult and expensive, due to hydrogen's low density. Even in this case there are different options, each one best suitable for different scenarios *(Figure 4)*. Generally, for large-scale transport, pipelines are the best option. In this regard, it could be convenient to blend hydrogen into the existing natural gas

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[27] Dickel Ralf (2020), *"Blue hydrogen as an enabler of green hydrogen: the case of Germany"*, OIES Paper: NG 159, Oxford Institute for Energy Studies

[28] For more details on the impact of carbon pricing on the green transition see: McWilliams B., Tagliapietra S., Zachmann G. (2020), *"Greening the recovery by greening the fiscal consolidation"*, Policy Brief 2020/02, Bruegel

[29] Mitrova T., Melnikov Y., Chugunov D. (2019), *"The hydrogen economy – a path towards low carbon development"*, SKOLKOVO Energy Centre, SKOLKOVO Moscow School of Management

[30] US Department of Energy, Office of Nuclear Energy (2020), *"Could Hydrogen Help Save Nuclear?"*, https://www.energy.gov/ne/articles/could-hydrogen-help-save-nuclear

[31] IEA (2019), *"The Future of Hydrogen: seizing today's opportunities"*, p. 69

pipeline networks. For instance, in the European Union there are projects to reconvert and reuse the natural gas infrastructure which connects Europe to North African countries.

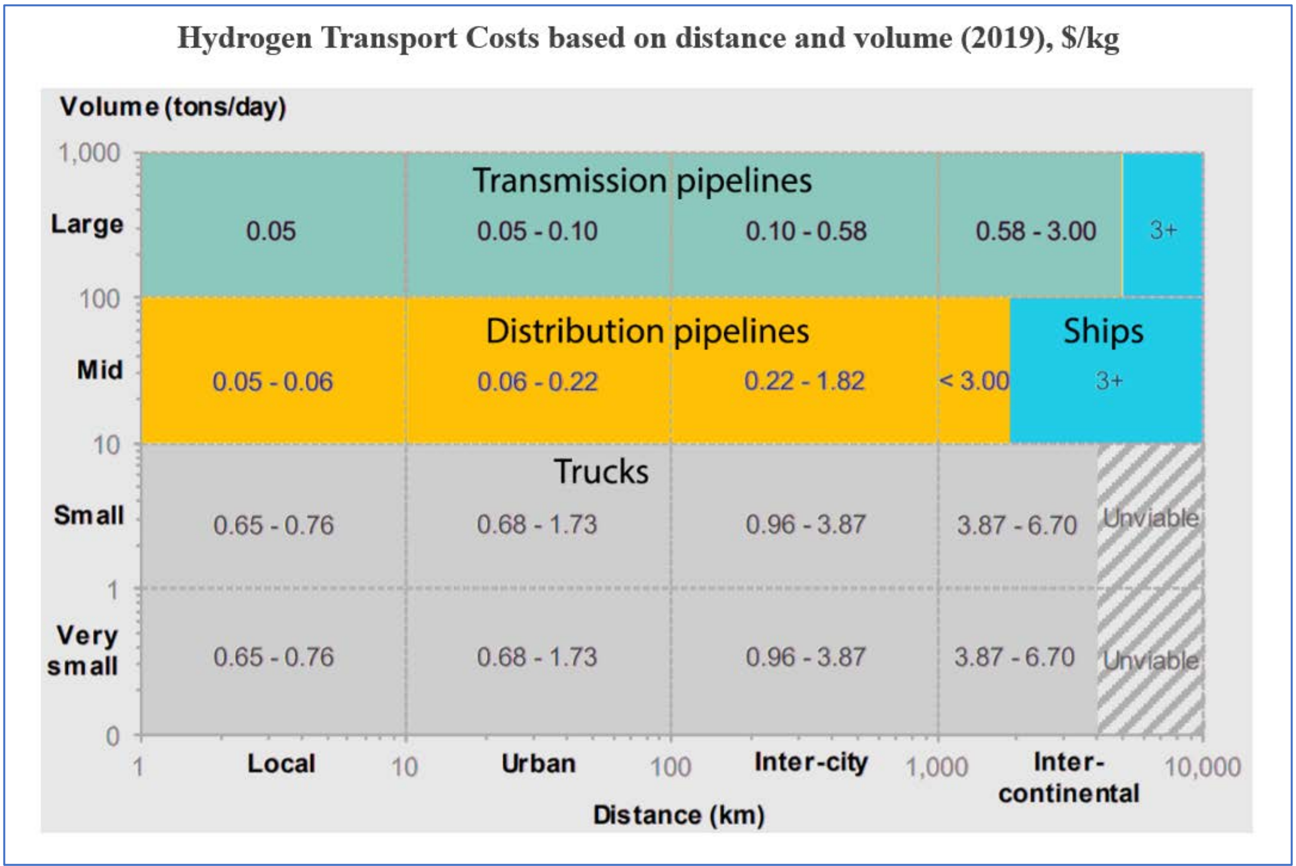

Figure 4

<u>Source</u>: Author's elaboration based on data from BloombergNEF (2020), *"Hydrogen Economy Outlook"*
Note: figures include the cost of movement, compression and associated storage (20% assumed for pipelines in a salt cavern).

Finally, these operations necessitate cross-border cooperation. Since, in certain regions, imported hydrogen is cheaper than domestic production, the future hydrogen economy will be shaped by the diplomatic relations between importer and exporter countries. International cooperation will be needed to build large infrastructures, supported by public-private partnerships. Therefore, building trust between governments in this emerging sector will be a prerequisite for future investments.

In terms of applications, the major obstacle will be the creation of new markets for hydrogen. Indeed, today, hydrogen is mostly used in certain industrial sectors, namely oil refining, chemicals and iron and steel. In all of these sectors, hydrogen is supplied using fossil fuels, with a high level of CO_2 emissions. In order to meet climate goals, these sectors should transition towards the use of low-carbon hydrogen – linked to elevated costs.
However, a future global hydrogen market should look beyond the existing industrial applications, expanding to other sectors thanks to hydrogen's high versatility. For instance, clean hydrogen offers promising potential in the buildings, transport, and power sectors, where it plays an important role in decarbonisation policy goals. Hydrogen also represents a viable solution to reduce carbon emissions in aviation and shipping, whose low-carbon fuel alternatives are constrained.

Around the world there are several pilot projects that are trying to unfold hydrogen's potential. Nonetheless, expanding the use of low-carbon hydrogen to completely new applications is a huge job. Even though there exist numerous opportunities, hydrogen has to compete with other clean energy options, which might be already rooted in the energy system – thus offering less uncertainty than hydrogen.

3.3 Need for international standards on hydrogen

The need for international standards and regulations on hydrogen represents a major obstacle to the development of a global hydrogen market. Since hydrogen is an emerging market, there are still no international standards on in its production and use, leading single countries to develop their own internal standards and regulations, or even unwritten and unclear rules[32]. This lack of a common regulation limits the diffusion of hydrogen, restraining its potential.

Therefore, developing a common international framework appears essential, to avoid free riding and unfair competition. Particularly, it is of key importance defining standard production definitions. Indeed, looking at the various hydrogen national plans, single countries have adopted different meanings for the same terms, with some countries having a "more flexible" approach on environmental issues. For instance, the term "low-carbon hydrogen" has a different CO_2 emissions threshold in different countries. Confusing terms is often used as a strategy to divert consumers from the real environmental impact of specific hydrogen production pathways.

Moreover, to ensure cross-border cooperation, it is necessary to agree on operational rules, harmonised safety standards, and the environmental impact of the technologies involved. If policymakers are committed to boost momentum for hydrogen, then they should promote multilateral fora for the creation of common methodologies and standards, defining the environmental impact of the full life-cycle hydrogen value chains.

For example, the European Union has recently proposed - in its 2020 hydrogen strategy – to expand international cooperation through international standardisation bodies and global technical regulations of the United Nations, collaborating under G20, with the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA), in order to "create further opportunities for exchange of experiences and best practices"[33].

It is yet not clear how the hydrogen market will develop, but fostering shared international standards is the first step towards the creation of a fairly competitive and well-functioning global market.

[32] IEA (2019), *"The Future of Hydrogen: seizing today's opportunities"*

[33] EU Commission (2020), *"A hydrogen strategy for a climate-neutral Europe"*, Brussels

4. Geopolitical implications of the future hydrogen economy

The energy market is changing, and thus the geopolitical chessboard. Since the acknowledgement of the climate consequences of an oil-based society, the energy market has shifted towards the gradual use of renewable energies, triggering deep geopolitical changes. The inevitable acceleration in the use of renewables will, in a way or another, modify the global configuration of power, altering relations between countries, drawing a new map of conflict risk regions, and favouring the emergence of new international actors.

In this new energy system, green hydrogen may play a crucial role. According to recent studies, renewable hydrogen could indeed secure up to 14% of the future global energy markets[34]. Therefore, the emergence of a hydrogen economy will presumably influence geopolitical dynamics.

In order to understand the current progress towards the implementation of a hydrogen global market, this chapter will firstly provide a brief overview of the most low-carbon hydrogen-advanced countries, and secondly it will show how the major global players – i.e. the United States, the European Union, China, Russia - are investing in this emerging sector. Finally, the chapter will analyse the possible geopolitical dynamics of a future hydrogen economy, focusing on how it could alter the geopolitical chessboard.

4.1 Low-carbon hydrogen pioneer countries[35]

Ranking the most advanced low-carbon hydrogen countries is not that easy. Low-carbon hydrogen - including green, blue, yellow, and turquoise hydrogen – is a newly emerged market, with different countries following different pathways towards the implementation of hydrogen projects, targeting different climate goals, and having different geopolitical interests. However, in order to offer an indication of the main countries which invest in low-carbon hydrogen, this paragraph will select four nations – including both future hydrogen exporters and importers - which are, more than others, committed to a low-carbon hydrogen economy.

4.1.1 Japan

Japan is committed to become the first "Hydrogen Society". With its 2017 Basic Hydrogen Strategy, Japan remains the most advanced country in terms of green hydrogen development projects, showing its leadership in hydrogen fuel-cell vehicle development, international hydrogen projects, and hydrogen trade.

Since the signing of the 2015 Paris Agreement, the Japanese Ministry of Economy, Trade and Industry has indeed increasingly invested in hydrogen, considered as one of the keys to decarbonise

[34] De Blasio N., Pflugmann F. (2020), *"Geopolitical and Market Implications of Renewable Hydrogen: New Dependencies in a Low-Carbon Energy World"*, Environment and Natural Resources Program, Belfer Center for Science and International Affairs, Harvard Kennedy School, Cambridge

[35] For a complete list of hydrogen' national strategies worldwide see table attached: Hydrogen main Strategies / Projects Worldwide

the national economy. Japan's goal is to establish itself as a green hydrogen hub, developing "the most efficient hydrogen energy management system"[36]. To this end, the government has launched the Basic Hydrogen Strategy, building a massive infrastructure for import and distribution of hydrogen. Moreover, aware of the need for international cooperation, Japan has also engaged industry stakeholders in Australia, Brunei, Saudi Arabia, and Norway for partnerships on the development of hydrogen projects[37]. For instance, METI and Saudi Aramco recently collaborated on a multi-industry partnership for the supply of blue hydrogen from Saudi Arabia to Japan[38], paving the way for future beneficial cooperation on hydrogen trade.

Furthermore, in March 2020, the Japanese government completed the Fukushima Hydrogen Energy Research Field, the world's largest renewable hydrogen production facility, which produces around 200 tons of clean hydrogen annually[39], using electricity from solar panels located around its perimeter.

Finally, to showcase its commitment to hydrogen, Japan decided to build the Olympic Village in Tokyo as a miniature hydrogen society, providing electricity through a hydrogen station, a hydrogen pipeline, and pure hydrogen fuel cells. Following the end of the Olympic Games, Japan will designate the area for residential and commercial use, and will employ the electricity produced by these facilities[36].

4.1.2 Australia

To date, Australia has established itself as the top green hydrogen producer. Thanks to the abundance of renewable energy resources, Australia has indeed the potential to support a large-scale hydrogen industry, producing low-carbon hydrogen and exporting it to neighbouring countries.

For this reason, recognizing hydrogen's potentialities in replacing fossil fuel exports, in 2019 the Australian government released the National Hydrogen Strategy, laying the foundation for Australia to become a key exporter of hydrogen[40]. According to the Australian Renewable Energy Agency (ARENA), "Australian hydrogen exports could contribute $1.7 billion per annum to the economy and provide 2,800 jobs by 2030"[41]. Thus, Australia has launched a series of international partnerships and engagement to encourage hydrogen trade, looking at Japan, South Korea, China, and Singapore as the preferred markets by 2025. In January 2020, Australia and Japan signed the Joint Statement on Cooperation on Hydrogen and Fuel Cells[42], fostering bilateral cooperation on hydrogen technologies and regulations, and paving the way for future hydrogen trade.

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[36] Japan Government (2020), "*Giant Leap Towards a Hydrogen Society*", https://www.japan.go.jp/tomodachi/2020/earlysummer2020/hydrogen.html

[37] Harding Robin (2020), "*Japan bets on ammonia as the fuel of the future*", Financial Times

[38] Ratcliffe Verity (2020), "*Saudi Arabia Sends Blue Ammonia to Japan in World-First Shipment*", Bloomberg, https://www.bloomberg.com/news/articles/2020-09-27/saudi-arabia-sends-blue-ammonia-to-japan-in-world-first-shipment

[39] Japanese Ministry of Economy, Trade and Industry (2020), "*Opening Ceremony of Fukushima Hydrogen Energy Research Field (FH2R) Held with Prime Minister Abe and METI Minister Kajiyama*", METI, https://www.meti.go.jp/english/press/2020/0309_001.html

[40] Australian Government (2020), "*National Hydrogen Strategy priorities and delivery*", Department of Industry, Science, Energy and Resources, https://www.industry.gov.au/news-media/climate-and-energy-news/national-hydrogen-strategy-priorities-and-delivery

[41] ARENA (2018), "*Hydrogen offers significant exporting potential for Australia*", Australian Renewable Energy Agency, https://arena.gov.au/news/hydrogen-offers-significant-exporting-potential-for-australia/

[42] Australian Government (2020), "*Australia, Japan agreement an exciting step towards hydrogen future*", Ministers for the Department of Industry, Science, Energy and Resources, https://www.minister.industry.gov.au/ministers/canavan/media-releases/australia-japan-agreement-exciting-step-towards-hydrogen-future

Moreover, ARENA has supported R&D in renewable hydrogen production, storage, and use, with the aim of reducing costs and improving hydrogen energy efficiency. In the last few years, it has funded several pilot projects[43], which are currently bearing fruit.

4.1.3 South Korea

South Korea is a hydrogen frontrunner. The first commercial fuel cell electric vehicle was created by Hyundai, a South Korean company; the largest fuel cell manufacturing plant was built by POSCO Energy, a South Korean energy firm; and one of the world's first hydrogen national plans was launched by the Korean government.

The South Korean government sees indeed in hydrogen a recipe for economic growth, which would shift the country to a low-carbon economy[44]. In 2019 the government agreed on a roadmap to a hydrogen economy, establishing long-term goals for the development of a hydrogen economy. The plan focused mainly on the production of fuel cell cars and large scale stationary fuel cells for power generation. Specifically, the roadmap aimed at producing 6.2 million units of fuel cell electric vehicles and building 1,200 refuelling stations by 2040.

In 2019 South Korea also unveiled the H_2 pilot city programme[45], a government-funded project aimed at transforming a few selected cities - Ansan, Ulsan, Wanju/Jeonju, Samcheok - into "hydrogen cities", building the necessary infrastructure to produce, distribute, and use hydrogen for heating, cooling, transport, and electricity supply.

More recently, in August 2020, South Korea's renewable energy company Hanwha Energy started commercial production at the world's first byproduct hydrogen-based fuel cell power plant[46]. The plant, with hydrogen extracted as a byproduct from petrochemical production, produces 400,000 MWh of electricity a year, representing one of the largest hydrogen facilities in the world, and an example of innovative technology.

Therefore, South Korea is at the forefront of the hydrogen industry development. Nonetheless, its strategy is not as environmentally-friendly as its neighbours' – Japan and Australia. The South Korean government has indeed embraced a vaguer low-carbon hydrogen strategy, aimed at generally expanding hydrogen production[47]. Only in a second phase, the government aims at reducing hydrogen's carbon footprint, developing a low carbon hydrogen market thanks to the country's expertise in technological innovation. The government has also considered importing clean hydrogen from overseas, including Australia and Norway.

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[43] For a complete list of the last funded projects see: ARENA (2020), *"ARENA Funded Hydrogen Projects and Reports"*, https://arena.gov.au/knowledge-bank/arena-funded-hydrogen-projects-and-reports/

[44] Stangarone, T. (2020), *"South Korean efforts to transition to a hydrogen economy"*, Clean Technologies and Environmental Policy, https://link.springer.com/article/10.1007/s10098-020-01936-6#citeas

[45] Edmond Charlotte (2019), *"South Korea is building 3 hydrogen-powered cities for 2022"*, World Economic Forum, https://www.weforum.org/agenda/2019/11/south-korea-green-energy-hydrogen-future-city-fossil-fuel-renewables/

[46] Mohanty S., Lee C. (2020), *"S Korea takes another step toward hydrogen economy with Hanwha's byproduct plant"*, SPGlobal Platts, https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/081820-s-korea-takes-another-step-toward-hydrogen-economy-with-hanwhas-byproduct-plant

[47] Kan Sichao (2020), *"South Korea's Hydrogen Strategy and Industrial Perspectives"*, Edito Energie, Ifri

4.1.4 European Union

The European Union has always been a leader in climate policies, implementing the Paris Agreement and adopting carbon-neutrality goals as part of its agenda. In July 2020, following its commitment to reach carbon neutrality by 2050, the EU decided to adopt a Hydrogen Strategy[48].
Even though the European Union is composed of diverse realities, with countries following different pathways towards climate neutrality, its common strategy sent a clear message, believing in the potential of hydrogen as a sustainable energy carrier. Particularly, the EU encouraged the production and use of green hydrogen, as a long-term alternative to fossil fuels. Part of the European Green Deal, the Hydrogen Strategy will contribute to consolidate the EU's global position as a norm and standard setter on energy transition, promoting its technological leadership, increasing its energy security, and strengthening partnerships with third countries.

Looking at specific states inside the EU, **Germany** undoubtedly represents the most advanced country on clean hydrogen development. A frontrunner in renewable energy, Germany has indeed urged the European Commission to conceive a comprehensive plan on hydrogen, following the need to build technology leadership in this emerging field.
In June 2020, a month before the release of the EU Hydrogen Strategy, the German government unveiled its own National Hydrogen Strategy[49]. To achieve the goal of producing 5 GW by 2030 and 10 GW by 2040, Germany invested €7 billion in new hydrogen businesses and research. Moreover, as part of the economic stimulus package, the government also provided €2 billion for hydrogen international partnerships, mainly in North Africa, where it has already concluded various agreements on common production facilities.

Apart from Germany, also other EU countries developed their own hydrogen roadmaps. In the weeks following the release of the EU Hydrogen Strategy, several states contributed to the European vision with specific pathways to foster low-carbon hydrogen production and use. Particularly, various countries – including France, Portugal, and Spain - included investments on blue and green hydrogen in their post Covid-19 recovery plans.
The EU Hydrogen Strategy, linked to funds from the EU Recovery Plan, represents an opportunity for Southern European countries, including Italy and Spain, which could become renewable hydrogen hubs, by importing hydrogen produced in North Africa from solar power and exporting it to other European countries, through the existing gas pipelines *(Figure 5)*.

For instance, in **Italy** hydrogen could account for 23% of Italian energy demand by 2050, reducing CO_2 emissions by 28% from current levels[50]. According to a Snam - McKinsey analytical report, Italy could import hydrogen from North Africa, at cost 14% below domestic production, and Italian gas infrastructure supports hydrogen's potential[51]. As a result, Snam, Europe's biggest gas pipeline operator and one of the major Italian companies, "has been experimenting with a 10% mix of hydrogen in its natural gas network"[50], with the result that it seems that the already existing natural gas grid can support the transport of hydrogen.

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[48] EU Commission (2020), *"A hydrogen strategy for a climate-neutral Europe"*, Brussels
[49] German Federal Ministry for Economic Affairs and Energy (2020), *"The National Hydrogen Strategy"*, https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html
[50] Reuters (2020), *"Italy can be clean energy hub with hydrogen imports from Africa, study says"*, https://www.reuters.com/article/us-italy-hydrogen-idUSKBN25W0JM
[51] Snam (2019) *"The Hydrogen Challenge: the potential of hydrogen in Italy"*, https://www.snam.it/en/hydrogen_challenge/potential_hydrogen_italy/

In addition, clean hydrogen also represents an opportunity for various Italian companies, which could reconvert to green industries. This includes the Ilva steelworks, for a long time at the center of a heated debate on its high levels of greenhouse gas emissions and air pollutants. As highlighted by the EU Commission's Vice-President Frans Timmermans (2020), Italy "can use EU funds to save Ilva in Taranto and produce clean steel". Thus, green hydrogen represents a unique opportunity for Italy, to relaunch its energy sector and, most importantly, to assume a leading role in the European hydrogen value chain.

4.2 Geopolitically most influential countries: how are they dealing with hydrogen?

The clean hydrogen economy has only recently started to emerge. To date, hydrogen has been used mainly for industrial activities, and its value chain has generally been limited to the production and use of grey hydrogen. In fact, the United States, China, and Europe are the largest consumers of hydrogen in refineries, representing around half of total refinery hydrogen consumption[52], and contributing to high levels of CO_2 emissions. The transition to a clean hydrogen economy would thus require huge investments, clear political will, and serious environmental commitments.

The previous paragraph analysed the most advanced countries in terms of low-carbon hydrogen development projects, but what about the world's most influential countries, i.e. China, Russia, the United States, and the European Union? How are they dealing with the hydrogen economy, and how green is their hydrogen?

China is the world leader in grey hydrogen, with hydrogen produced mainly from coal for the production of ammonia. Today, coal represents indeed the cheapest option for the production of hydrogen, with costs amounting to around $ 1/kgH_2[52]. CHN Energy, China's largest power company, is also the world's major hydrogen production firm, producing around 8 MtH_2/yr, which correspond to 12% of global hydrogen production[52].

In the last decade, the People's Republic of China - probably also spurred by the competition with its neighbour Japan – has started to invest in low-carbon alternatives to grey hydrogen, launching various low-carbon hydrogen demonstration projects and adopting thousands of hydrogen fuel cell electric buses and trucks. Low-carbon hydrogen could play an important role in the achievement of the recently-announced China's commitment to become carbon-neutral by 2060[53]. Nevertheless, more on this issue will be discovered after the upcoming publication of the 14th five-year plan.

Currently, the most-competitive option for the production of low-carbon hydrogen is given by the use of coal with CCS, but in the long-term China could also utilise its renewable energy sources, such as wind and solar, for the production of green hydrogen[54]. Moreover, China has the opportunity to integrate hydrogen applications to coastal hubs close to offshore wind and solar PV in South East China, trading low-carbon hydrogen with its neighbours.

Russia has hitherto not developed a hydrogen industry. This is the case mainly for two reasons, linked to Russia's position in the energy market. First of all, Russia is a world leader in

[52] IEA (2019), *"The Future of Hydrogen: seizing today's opportunities"*, Report prepared by the IEA for the G20, International Energy Agency, Japan, https://www.iea.org/reports/the-future-of-hydrogen

[53] Regan Helen (2020), *"China will become carbon neutral by 2060, Xi Jinping says"*, CNN, https://edition.cnn.com/2020/09/22/china/xi-jinping-carbon-neutral-2060-intl-hnk/index.html

[54] For details on production of hydrogen from solar and wind see: "Production of hydrogen and ammonia from solar and wind in China" in IEA (2019), *"The Future of Hydrogen: seizing today's opportunities"*, pp. 62-63

hydrocarbons export, trading gas, oil, and coal around the globe. Thus, for Russia developing a hydrogen market is not economically and politically convenient. Secondly, the country does not have a strong climate agenda, with decarbonisation policies introduced only in the last few years.
Only recently, the Russian government has begun exploring hydrogen strategies, probably prompted by the necessity to regulate this emerging market. In July 2020, the Russian Ministry of Energy has prepared a draft plan for the development of Russian hydrogen energy for the period up to 2020-2024, supporting the "implementation of priority pilot projects in the field of hydrogen production, including the creation of pilot plants"[55], and envisioning export of 200,000 tonnes of hydrogen by 2024, and 2 million tonnes by 2035.
The Russian government has indeed understood the necessity to look into the hydrogen economy, which might challenge traditional energy sources in the next 20-30 years. Particularly, it has been the EU Hydrogen Strategy which has forced Russia to start developing new technologies for the production of low-carbon hydrogen[56]. Gazprom and Rosatom, the biggest Russian energy companies, are already working on technologies for the production of low-carbon hydrogen, considering the possibility of exporting it to Europe through the existing pipelines[57]. The carbon footprint of Russia's electricity production is already relatively low if compared to the world average, with electricity carbon content less than in the US, China, and India[57]. Thus, Russian companies mainly count on the possibility of using the already existing low-carbon electricity to produce hydrogen. Specifically, they are investing in blue and yellow hydrogen, using steam methane reforming with CCS and nuclear energy.

The **United States** is already highly involved in the hydrogen economy. As previously mentioned[58], the same term "hydrogen economy" was firstly introduced in the 1970s by US Universities, where several academics studied the potential of hydrogen in replacing fossil fuels.
Interest in hydrogen grew even further in the aftermath of 9/11, when the need for national security prompted the country to look for energy independence. As highlighted by the United States Department of Energy (2002), "the tragic events of September 11, 2001, remind every American of the danger of reliance on oil imports from politically unstable countries, some of which have opposing interests to those of the United States. […] Hydrogen is a versatile energy carrier that could be produced entirely from domestic sources of fossil fuel (e.g., natural gas and coal with capture and sequestration of carbon dioxide), renewable (e.g., solar, wind, and biomass), and nuclear energy, in large quantities. Its use as a major energy carrier would provide the United States with a more diversified energy infrastructure"[59].
Nowadays, the United States remains deeply engaged in the hydrogen economy. In fact, the US is the country with more fuel cells vehicles, which account for about half of registered FCEVs, followed by Japan (25%), the European Union (11%, primarily in Germany and France) and Korea

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[55] Teller Report (2020), *"The Ministry of Energy prepared a draft plan for the development of hydrogen energy"*, https://www.tellerreport.com/business/2020-07-22-the-ministry-of-energy-prepared-a-draft-plan-for-the-development-of-hydrogen-energy.ryXGDWUxv.html
[56] TASS (2020), *"Hydrogen to challenge Russian gas at its biggest market within 15-30 years, say experts"*, TASS Russian News Agency
[57] Mitrova T., Melnikov Y., Chugunov D. (2019), *"The hydrogen economy – a path towards low carbon development"*, SKOLKOVO Energy Centre, SKOLKOVO Moscow School of Management
[58] For details see the chapter on "Previous waves of enthusiasm for hydrogen: will this time be different?"
[59] US Department of Energy (2002), *"A National Vision of America's Transition to a Hydrogen Economy – to 2030 and beyond"*, Toward a More Secure and Cleaner Energy Future for America

(8%)[60]. In 2016 the United States Department of Energy also unveiled the H2 @ Scale initiative, exploring the potential for wide-scale hydrogen production and use across energy sectors[61].
Nevertheless, almost all of the hydrogen produced in the United States continues to be used for refining petroleum, treating metals, producing fertilizer, and processing foods – releasing high levels of CO_2 emissions -, with California, Louisiana, and Texas being the major hydrogen-producing states[62]. The United States, with its long history of research in the field of hydrogen, continues to mainly invest in the production of blue and yellow hydrogen, leaving green hydrogen a bit behind.
The production of blue hydrogen has been incentivized by the 45Q tax credit, that rewards the storage of CO_2 in geological storage sites. The United States has indeed the largest salt cavern hydrogen storage system, which can store around 30 days of hydrogen output from a nearby steam methane reformer (between 10 and 20 thousand tonnes of H_2 (ktH_2)) to support the supply and demand for refining and chemicals[63].
Regarding yellow hydrogen, the production of hydrogen from nuclear energy has often been presented as a promising solution, given that it could relaunch nuclear power plants. For instance, ten nuclear reactors could produce about 2 million tonnes annually or one-fifth of the current hydrogen used in the United States[64].
Looking at the single states which most invest in hydrogen, **California** definitely leads the way in low-carbon hydrogen. Indeed, with its decarbonization targets, California has heavily invested in research and development of low-carbon hydrogen projects. Recently, in May 2020, the US state announced the construction of one of the world's biggest low-carbon hydrogen production facilities in Lancaster. The plant, managed by SGH2 Energy Global company (Solena Group), will use plastics and recycled paper as a feedstock to produce up to 3.8 million kilograms of hydrogen per year[65].

The **European Union**, as mentioned in the previous chapter[66], aims at becoming a world leader in green hydrogen. The European Commission's hydrogen strategy represents an ambitious goal, given that it aims at making hydrogen an integral part of the future energy mix, accounting for 13-14% of Europe's energy mix by 2050 – now it is only 2%. The European interest for green hydrogen results from its commitment to become carbon neutral by 2050. Thus, the EU seeks to represent itself as the major global player in renewable energy, developing the most advanced technologies and pursuing innovative policies. Moreover, the EU seeks to diversify its energy sources, becoming independent from oil and natural gas imports, and enhancing security of energy supply.
The European Union also counts on partnerships with third countries for imports of renewable hydrogen, mainly using the existing gas pipelines which connect Southern Europe to North Africa. Indeed, the existing infrastructure could be easily reconverted for hydrogen transport, allowing the

[60] IEA (2019), *"The Future of Hydrogen: seizing today's opportunities"*, Report prepared by the IEA for the G20, International Energy Agency, Japan, https://www.iea.org/reports/the-future-of-hydrogen
[61] US Department of Energy, Office of Energy Efficiency and Renewable Energy (2020), *"H2@Scale"*, https://www.energy.gov/eere/fuelcells/h2scale
[62] United States Department of Energy (2020), *"Hydrogen Production and Distribution"*, Alternative Fuels Data Center, https://afdc.energy.gov/fuels/hydrogen_production.html
[63] IEA (2019), *"The Future of Hydrogen: seizing today's opportunities"*, Report prepared by the IEA for the G20, International Energy Agency, Japan, https://www.iea.org/reports/the-future-of-hydrogen
[64] United States Department of Energy, Office of Nuclear Energy (2020), "Could Hydrogen Help Save Nuclear?", https://www.energy.gov/ne/articles/could-hydrogen-help-save-nuclear
[65] SGH2 Energy (2020), *"World's Largest Green Hydrogen Project to Launch in California"*, https://www.sgh2energy.com/worlds-largest-green-hydrogen-project-to-launch-in-california
[66] For details see chapter on: *"Low-carbon hydrogen pioneer countries"*

EU to import low-cost hydrogen from renewables-abundant countries. As recognized by the European Commission, "Africa, due to its abundant renewables potential and in particular North Africa due to geographic proximity, is a potential supplier of cost-competitive renewable hydrogen to the EU requiring that the deployment of renewable power generation in these countries strongly accelerates"[67].

4.3 The geopolitical chessboard: how renewable hydrogen will influence relations between states

It is hard to imagine how a decarbonized economy will look like. In the long-run, the replacement of fossil fuels with renewable energy sources will probably shake up not only the energy industry, but also geopolitical dynamics. As highlighted by the International Renewable Energy Agency , "just as fossil fuels have shaped the geopolitical map over the last two centuries, the energy transformation will alter the global distribution of power, relations between states, the risk of conflict, and the social, economic and environmental drivers of geopolitical instability"[68].
If the hydrogen economy will take root, it will probably contribute - together with other carbon-free energy sources - to create a new geopolitical scenario, creating a new map of importers and exporters, redrawing alliances and rivalries between countries, and fostering new international actors.
While most of the research has focused on the technical implications of the future hydrogen economy, little attention has been devoted to geopolitical dynamics. Therefore, the aim of this paragraph is to analyse the main geopolitical implications of the future hydrogen economy, focusing firstly on how it will alter relations between states, secondly on the possible future agreements on hydrogen trade, and finally on its impact on the Global South.

First of all, the hydrogen economy will alter dependencies between states. In this regard, it has been argued that a future hydrogen economy could have the effect of ***"democratize" the energy system***. Indeed, green hydrogen - produced through the electrolysis of water, with electricity from renewable sources – could, at least theoretically, be produced almost everywhere. Thus, various scholars have argued that hydrogen could democratize the energy landscape by disrupting the hegemony of fossil fuels-rich states. However, this positive assumption remains highly unlikely. While it is certainly true that renewable energy sources, and thus hydrogen produced through them, have the potential to decentralize the energy system, it is also true that the real economy does not work in this way. Most probably, the future hydrogen economy will be moulded by trade in renewable hydrogen, following comparative advantages. Thus, even if a country can theoretically produce hydrogen from domestic sources, it will choose to benefit from international trade.
For these reasons, the future hydrogen economy will probably create a new class of importer and exporter countries. The role countries will likely adopt will be based on their resource endowment - i.e. availability of renewable energy sources and freshwater - and infrastructure potential[69] *(Figure 6 and Table 1).*

[67] EU Commission (2020), *"A hydrogen strategy for a climate-neutral Europe"*, Brussels
[68] IRENA (2019), *"A New World: the Geopolitics of the Energy Transformation"*, International Renewable Energy Agency, p.12
[69] De Blasio N., Pflugmann F. (2020), *"Geopolitical and Market Implications of Renewable Hydrogen: New Dependencies in a Low-Carbon Energy World"*, Environment and Natural Resources Program, Belfer Center for Science and International Affairs, Harvard Kennedy School, Cambridge

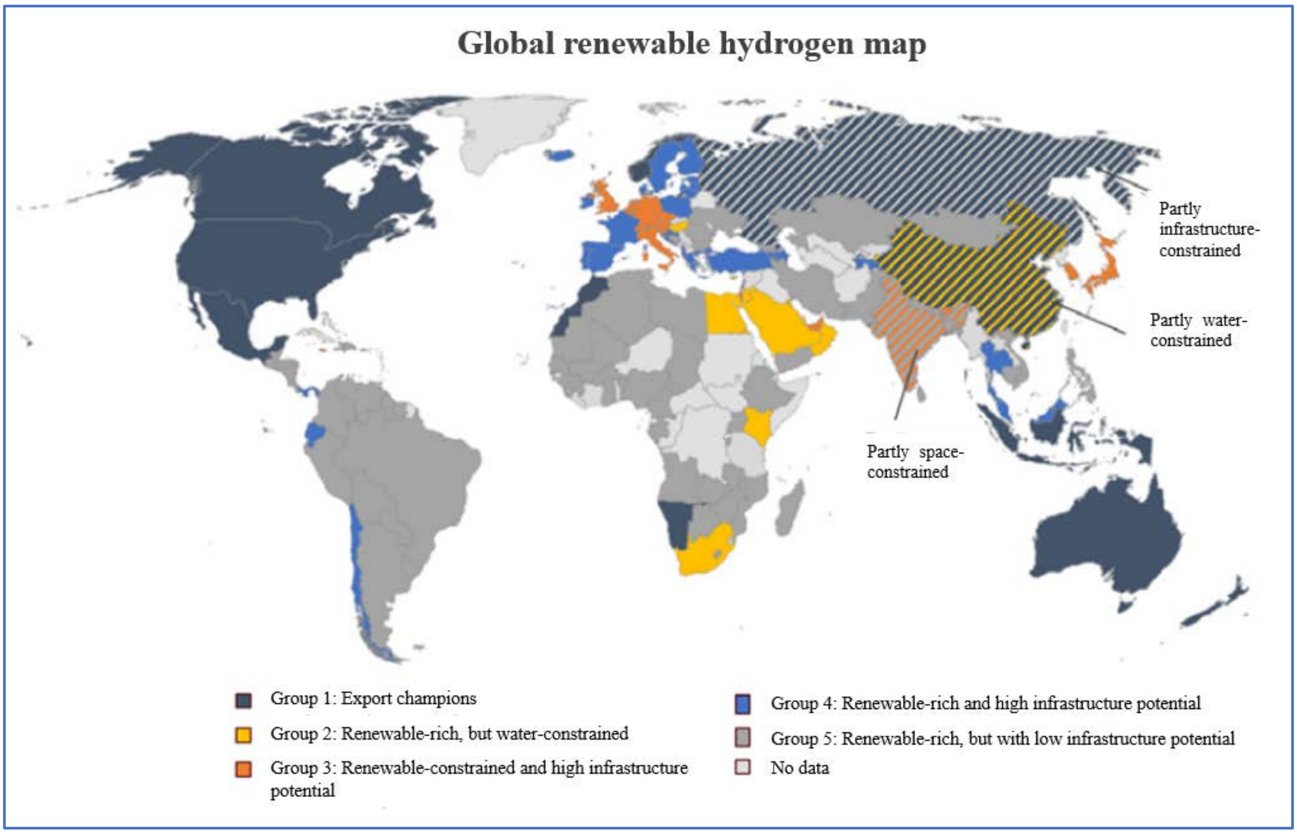

Figure 6

Note: the figure divides countries in groups 1 to 5, based on their resource endowment

Source: De Blasio N., Pflugmann F. (2020), "*Geopolitical and Market Implications of Renewable Hydrogen: New Dependencies in a Low-Carbon Energy World*", Environment and Natural Resources Program, Belfer Center for Science and International Affairs, Harvard Kennedy School, Cambridge

#	Group	Resource endowment		Infrastructure potential	Example countries
		Renewable energy resources	Renewable freshwater sources		
1	Export champions with vast renewable energy and water resources, as well as high infrastructure potential	+ +	+	+	Australia, United States, Morocco, Norway
2	Renewable-rich, but water-constrained nations with high infrastructure potential	+ +	- -	+	Saudi Arabia, potentially China
3	Renewable-constrained nations with high infrastructure potential	-	+	+	Parts of the EU, Japan, Korea
4	Resource-rich nations with high infrastructure potential	+	+	+	Turkey, Spain, Thailand
5	Resource-rich countries with low infrastructure potential	+	+ / -	-	Most parts of South America

Table 1

Legend: Abundant/very high (+ +); Available/high (+); Poorly available/constrained (–); Scarce/highly constrained (– –)

Source: Author's elaboration based on data from *De Blasio N., Pflugmann F. (2020), "Geopolitical and Market Implications of Renewable Hydrogen: New Dependencies in a Low-Carbon Energy World"*, Environment and Natural Resources Program, Belfer Center for Science and International Affairs, Harvard Kennedy School, Cambridge

Certain countries are already investing in their potential as importer or exporter countries. For instance, the European Union, Japan and South Korea expect to import green hydrogen from countries with comparatively cheap, abundant renewables, which could help reducing the cost of the energy transition and pressures on domestic resources - i.e. space on sea and land[70]. On the other side, countries such as Australia, Chile, and New Zealand focus on the possibility of becoming exporters of green hydrogen, thanks to their renewables' abundance.

Particularly, among possible future clean hydrogen exporters, Chile emerges as a major player in the fuel's future. Through the development of wind, hydroelectric, and solar projects, the South American country could indeed transform its economy, which is currently heavily reliant on fossil fuel imports. Moreover, Chile has the potential to export as much as green hydrogen as it does minerals, producing 25 million Mt/year of green hydrogen by 2050, and generating exports worth

[70] Van de Graafa Thijs, Overlandb Indra, Scholtenc Daniel, Westphald Kirsten (2020), *"The new oil? The geopolitics and international governance of hydrogen"*, Energy Research & Social Science 70 (2020) 1016672, Elsevier

more than $30 billion[71]. According to a McKinsey report[72], Chile could become a highly competitive player in the future green hydrogen market, delivering hydrogen to Korea, Japan, and maybe China, in addition to supplying markets in North America and Western Europe.
At present, several energy companies, including the Italian Enel, are working on pilot plants to produce renewable hydrogen in Chile. For instance, Enel is exploring the possibility of installing a hydrogen production plant, powered by wind energy, in Chile's southernmost region of Magallanes[73]. The plant could enter production in 2022, becoming the first green hydrogen plant in Chile, and one of the largest in Latin America.

Contemporarily, fossil-fuels rich states have to adapt to the energy transition, diversifying their economies and investing in renewable energy, in order to prevent a future economic disruption. For instance, countries in the Middle East have to invest in their position as strategic countries in the Global Sun Belt, taking advantage of the availability of abundant, low-cost solar - for producing green hydrogen - , underground storage options for CCS - for producing blue hydrogen - , and geographic location, is ideal to serve both European and Asian markets[70]. Nonetheless, to become renewable hydrogen exporters, these countries should necessarily also invest in desalination capacity, essential to produce hydrogen, given freshwater scarcity in the region.
In this regard, Saudi Arabia has recently announced its commitment to develop a clean hydrogen industry. As part of Vision 2030 and with the goal of diversifying the Saudi economy, the Gulf state has recently unveiled a plan for the building of a huge green hydrogen plant. The plant, based in NEOM, will see cooperation from the city of NEOM, a mega-city model for sustainable living, Air Products, a US industrial gas and chemical company, and Acwa Power, a Saudi Arabian power and desalination utility, and will produce 650 tons of green hydrogen daily, enough to run around 20,000 hydrogen-fuelled buses[74]. Moreover, Saudi Arabia has recently started to explore hydrogen trade options, cooperating mainly with Japan for future blue hydrogen export.

Secondly, the hydrogen economy will encourage new international agreements on hydrogen trade. Indeed, as previously mentioned, countries will trade renewable hydrogen based on comparative advantages. As a consequence, countries will be prompted to create new alliances, making agreements on hydrogen import / export, and creating regional and transregional networks. Various countries have already engaged in the so-called ***hydrogen diplomacy***, exploring the possibility of large-scale hydrogen trade.
For instance, Germany has recently signed a cooperation agreement with Morocco, with the goal of developing green hydrogen production, and cooperating on research and development of renewable hydrogen projects[75]. In addition, Morocco and Germany have already announced the development

[71] Azzopardi Tom (2020), *"Chilean minister says future hydrogen industry to rival copper"*, SP Global Platts, https://www.spglobal.com/platts/en/market-insights/latest-news/metals/072820-chilean-minister-says-future-hydrogen-industry-to-rival-copper
[72] McKinsey & Company (2020), *"Perspective on Hydrogen"*, https://energia.gob.cl/sites/default/files/clemens_muller-falcke_de_mckinseyco.pdf
[73] Azzopardi Tom (2020), *"Enel advances Chile's first green hydrogen project"*, SP Global Platts, https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/100220-enel-advances-chiles-first-green-hydrogen-project
[74] Air Products (2020), *"Air Products, ACWA Power and NEOM Sign Agreement for $5 Billion Production Facility in NEOM Powered by Renewable Energy for Production and Export of Green Hydrogen to Global Markets"*, https://www.airproducts.com/company/news-center/2020/07/0707-air-products-agreement-for-green-ammonia-production-facility-for-export-to-hydrogen-market
[75] Guessous Hamza (2020), *"Morocco First to Partner with Germany to Develop Green Hydrogen Sector"*, Morocco World News, https://www.moroccoworldnews.com/2020/06/305441/morocco-first-to-partner-with-germany-to-develop-green-hydrogen-sector/

of two projects: the “Power-to-X” project for the production of green hydrogen, proposed by the Moroccan Solar Energy Agency; and a research platform on “Power- to-X”, aimed at sharing knowledge and skills between the two countries, in partnership with the Institute for Research in Solar Energy and New Energies.

This agreement constitutes a promising example of future cross-country renewable hydrogen trade. Particularly, Morocco - such as other North African countries – is well-suited to become a key supplier of clean hydrogen to European countries. As highlighted in a 2019 study for Morocco’s Energy Ministry, Frauenhofer ISI, “Morocco’s strategic geographical proximity to Europe, along with its exceptional potential in wind and solar energy, particularly in the south of the country, as well as its current and future port and gas infrastructure, makes it a potential supplier of green molecules with very high added value”[76]. A hydrogen economy could thus offer the opportunity to strengthen diplomatic ties with third countries.

To provide further example, in 2019 South Korea and Norway agreed to strengthen ties in hydrogen energy, signing a Memorandum of Understanding “to cooperate in hydrogen energy to make the most of Korea’s strength in hydrogen-powered vehicles and Norway’s in production and supply capabilities”[77].

In August 2020, Portugal and the Netherlands signed a Memorandum of Understanding[78] to develop a green hydrogen export-import value chain. Green hydrogen, produced in Portugal, would be transported to the Netherlands and its hinterland via the ports of Sines and Rotterdam.

Thirdly, the hydrogen economy will impact on the relations between developed countries and the Global South. The way it will influence this relationship will depend on the real commitment to build a different energy system, based on equal partnership.

The fight against climate change has prompted several nations to question an economic system based on oil, rethinking the actual relationship between human beings and the environment. However, this new mindset should not be limited to promote sustainable development towards the environment. On the contrary, it should foster sustainable development also towards other human beings. Specifically, it should prompt developed countries to adopt a different, more inclusive approach towards the Global South.

In fact, the green revolution - and thus the hydrogen revolution - carries a risk of ***green colonialism***, i.e. the risk of considering developing countries solely as the providers of raw material and, in this case, green hydrogen. As climate change comes to the forefront of international politics, there is indeed the risk that developed countries externalize their carbon-intensive activities in the Global South, decarbonising their domestic economies, but contemporarily exploiting developing nations’ resources and labour. As society makes progress towards the climate emergency, it is fundamental that it does not internalize the colonial principles that have lacerated our societies. The industrial revolution was sustained by the “infrastructure of slavery and colonialism; a green version of this is no better”[79]. Thus, renewable hydrogen development should not be done at the expense of indigenous people. Moreover, inclusive societies and equal partnerships would benefit

[76] Eichhammer et al. (2019), *“Study on the Opportunities of “Power-to-X” in Morocco”*, Frauenhofer ISI

[77] Ji-hye Shin (2019), *“Korea, Norway to cooperate on hydrogen, shipbuilding”*, The Korea Herald, http://www.koreaherald.com/view.php?ud=20190613000650

[78] Government of the Netherlands (2020), *“Memorandum of understanding between Portugal and the Netherlands concerning green hydrogen”*, https://www.government.nl/documents/publications/2020/09/23/memorandum-of-understanding-between-the-netherlands-and-portugal-concerning-green-hydrogen

[79] Gebrial Dalia (2019), *“As the left wakes up to climate injustice, we must not fall into green colonialism”*, The Guardian, https://www.theguardian.com/commentisfree/2019/may/08/left-climate-injustice-green-new-deal

both parties, contributing to increase mutual trust, which is at the very base of every beneficial and durable trade agreement.

For instance, Germany has recently signed an agreement with the Democratic Republic of Congo over the potential production of clean hydrogen[80]. The Memorandum of Understanding includes a project for the building of a hydrogen plant on Congo's coast, whose clean hydrogen would then be shipped to Germany. Nonetheless, in a country where the vast majority of the population does not have access to electricity, it seems questionable to export the few energy sources that the country owns. This project, such as many others, constitutes the perfect example of green colonialism, in addition to representing a non-optimal allocation of the available resources in the fight against climate change. Indeed, the Democratic Republic of Congo is the third largest population in the world without access to electricity, with only 1.6 million over 10 million households having access to electricity[81]. For this reason, on one side, the Congolese government should focus on producing and distributing electricity, instead of exporting green hydrogen and leaving its own population without access to energy sources. On the other side, the German government should strengthen partnerships on green hydrogen export only with those states that have a surplus of energy sources, while encouraging developing countries to produce and use their domestic energy sources.

[80] Bax Pauline (2020), "*Congo Hydrogen Plant Being Considered by European Turbine Makers*", Bloomberg, https://news.bloomberglaw.com/environment-and-energy/congo-hydrogen-plant-being-considered-by-european-turbine-makers

[81] World Bank (2020), "*Increasing Access to Electricity in the Democratic Republic of Congo: Opportunities and Challenges*", World Bank, Washington, DC, https://openknowledge.worldbank.org/handle/10986/33593

5. Conclusions – Policy Recommendations

Clean hydrogen has often been presented as the holy grail of decarbonization. In the last years, the urgent need to find alternatives to fossil fuels has contributed to hydrogen's representation as a promising solution, able to break the hegemony of fossil fuels and mitigate the shortcomings of renewable energy sources.

However, as demonstrated in this working paper, the hydrogen economy is still far from becoming reality. Investments in green hydrogen technologies and projects have certainly increased over the last decade, but there still remains a high number of unresolved issues, relating to technical challenges and geopolitical implications.

Here are some policy recommendations to boost momentum in green hydrogen:

- **Consider clean hydrogen an integral part of the energy transition**
  In the long-term, clean hydrogen could play a significant role in the energy system. Particularly, it could complement renewable energy sources, by mitigating their shortcomings and replacing carbon-rich fuels in "hard-to-abate" sectors. Governments and the private sector should take advantage of this unprecedented momentum to strengthen their efforts towards the hydrogen economy.

- **Green hydrogen should be part of a wider strategy to fight climate change worldwide: developed countries should avoid externalising carbon-intensive activities to third countries**
  Green hydrogen can help decarbonise the world economy. Thus, its use should not be limited to developed countries, but it should be fostered worldwide. Producing green hydrogen in countries with comparatively cheap, abundant renewables - mainly located in the Global South -, can help reduce the cost of the energy transition. However, producer countries should benefit from their own production of clean hydrogen, and not entirely exporting it to developed countries. Indeed, from an environmental point of view, it has little sense decarbonising Western nations' economies, while continuing to emit high levels of CO_2 in the Global South: climate change can be fought only by diminishing the worldwide CO_2 emissions, not by bringing them to third countries. Thus, developed countries should avoid externalising their carbon-intensive activities, while positively collaborating with third countries for a global reduction of greenhouse gases.

- **Focus on green hydrogen as the only long-term goal**
  Green hydrogen, with near zero carbon emissions, is the only sustainable solution in the long-term. Thus, governments should always target renewable hydrogen in their long-term hydrogen strategies. Nonetheless, in the short – medium term, also low-carbon hydrogen could be implemented. Indeed, given the current high costs of clean hydrogen and its low energy efficiency, low-carbon hydrogen plays an important role in a transition phase.

- **Invest in research and development**
  Green hydrogen is not yet economically competitive, mainly due to its high production costs and its low energy efficiency. Investing in research and development appears as the only way to bring down costs, encouraging the emergence of a clean hydrogen economy.

- **Encourage the development of a clean hydrogen value chain**
  Currently, the hydrogen value chain is dominated by fossil fuels, with only a few pilot projects on low-carbon hydrogen. Governments should encourage the creation of clean hydrogen supply, handling, and demand chains, by developing new infrastructures, reconverting natural gas pipeline systems, creating new markets for hydrogen, transitioning grey hydrogen industrial sectors towards the use of low-carbon hydrogen, and fostering cross-border cooperation.

- **Develop a hydrogen common international framework**
  Currently, the lack of a common regulation limits the diffusion of hydrogen, restraining its potential. Therefore, national governments should define standard production definitions, and promote multilateral fora for the creation of common methodologies and standards, defining the environmental impact of the full life-cycle hydrogen value chains. This step is essential to guarantee a fairly competitive and well-functioning global hydrogen market.

- **Unlock new trade opportunities and foster cooperation with third countries**
  Green hydrogen can be produced at lowest cost in countries with abundance of renewable energy sources and low project development costs. Benefiting from comparative advantage, these countries could export renewable hydrogen to countries that lack domestic affordable hydrogen production. Thus, countries should cooperate in order to benefit from hydrogen trade.

- **Avoid falling in the trap of green colonialism**
  The hydrogen economy has the potential to redraw relations between developed countries and the Global South, by creating new inclusive, and equal partnerships. Developed countries should not be tempted to commit the same mistakes of the past, i.e. considering developing countries solely as the providers of raw material. Thus, renewable hydrogen development should not be done at the expense of indigenous people.

- **Fossil fuels-rich states should view green hydrogen as an opportunity to diversify their economies**
  Fossil-fuels rich states, whether they will like it or not, will have to adapt to the energy transition. Hence, in order to prevent a future economic disruption, they should diversify their economies by developing the production of new energy sources, including green hydrogen. Countries in the Middle East and North Africa could benefit from their great solar potential and strategic geographical position between European and Asian markets. However, to become green hydrogen exporters, they should also invest in desalination capacity.

- **The geopolitically most influential countries should invest in green hydrogen technologies, encouraging the emergence of hydrogen national markets**
  If the hydrogen economy takes root, it will probably contribute to creating a new geopolitical scenario. For this reason, if the major global players want to have a voice in this emerging market, they should start developing their own hydrogen national strategies, investing in research and development.

- **The European Union should take advantage of its "climate leadership" to promote its high standards on hydrogen production**
  The European Union has always been a leader in renewable energy, and with its 2020 Hydrogen Strategy it aims at consolidating its leadership also in green hydrogen. The European Union should thus strengthen cooperation among member states to become a norm and standard setter also on hydrogen, by promoting its technological leadership, increasing its energy security, and strengthening partnerships with third countries.

- **South European countries, including Italy, should develop and pursue national hydrogen strategies, with the ultimate goal of becoming renewable hydrogen hubs**
  The EU Hydrogen Strategy, linked to the EU Recovery Fund, represents a unique opportunity for Southern European countries, including Italy, to revamp their strategic position in the European Union. Particularly, the Italian government should look at renewable hydrogen as an opportunity to strengthen the Italian commitment to environmental policies, and to relaunch its strategic geopolitical position as the natural bridge between Europe and North Africa. In this regard, Italy should use renewable hydrogen to cleaner domestic "hard-to-abate" industries, and to distribute green hydrogen to other European countries - by importing it from North Africa through the existing gas pipelines.

Authors' Contribution

Rossana Scita: conceptualization (lead), investigation, visualization, writing – original draft, writing – review & editing (lead).

Pier Paolo Raimondi: conceptualization (support), supervision (equal), writing – review& editing (support).

Michel Noussan: conceptualization (support), supervision (equal), writing – review & editing (support).

Appendix: Hydrogen main Strategies / Projects Worldwide

Country	Strategy	Objectives / Measures	References
Argentina	Memorandum of Cooperation with Japan (2019)	• Cooperating in the development of hydrogen as a clean fuel • Promote investments in green H_2, using Argentina's wind resources	https://www.cancilleria.gob.ar/en/announcements/news/argentina-and-japan-work-together-development-hydrogen-clean-fuel
Australia	Australia's National Hydrogen Strategy (2019)	• Being a major global player in clean hydrogen by 2030 • To 2025: foundations and demonstrations • From 2025: large scale market activation	https://www.industry.gov.au/data-and-publications/australias-national-hydrogen-strategy
	South Australia's Hydrogen Action Plan (2019)	• Become a net 100% renewable energy generator during the 2030s • Over $1 million towards a landmark study to identify optimal locations for renewable hydrogen production and export infrastructure.	https://www.renewablessa.sa.gov.au/topic/hydrogen
	Queensland Hydrogen Industry Strategy 2019-2024 (2019)	• Develop a renewable hydrogen industry in Queensland • AUD 15 million to support hydrogen projects	https://www.dsdmip.qld.gov.au/resources/strategy/queensland-hydrogen-strategy.pdf
Austria	Renewable hydrogen: flagship project 7 of the Austrian Climate and Energy Strategy for 2030 (2018)	• Support investments, research and development • Tax advantage for hydrogen (Tax Reform Act 2020) • Goal of developing a national hydrogen strategy to complement the European Hydrogen Strategy	https://www.bmlrt.gv.at/service/publikationen/umwelt/mission-2030-austrian-climate-and-energy-strategy.html
	Integrated National Energy and Climate Plan for Austria (2019)	• Hydrogen part of the Austrian strategy to achieve carbon neutrality	https://ec.europa.eu/energy/sites/ener/files/documents/at_final_necp_main_en.pdf
Belgium	Regional Initiatives: TWEED Cluster, Walloon Region	• H_2 mobility (refuelling stations) • Strategy 2030 and 2050: clean H_2 gradual rise	https://clusters.wallonie.be/tweed-en/

	(2018) Waterstofnet, Flanders (2017)	• Support EU Hydrogen Strategy	 https://www.waterstofnet.eu/en
Brazil	Hosted and supported the 22nd World Hydrogen Energy Conference (2018)	• Foster the interest for new scientific and technological activities on hydrogen	https://www.ctc-n.org/news/22nd-world-hydrogen-energy-conference-brazil
Canada	Hydrogen Pathways - Enabling a Clean Growth Future for Canadians (2019)	• 10 high-level actions to make hydrogen and fuel cell technologies part of a clean growth solution	https://www.nrcan.gc.ca/energy-efficiency
Chile	Conference on "Green Hydrogen National Strategy" (2020)	• Elaborate a green hydrogen strategy • Chile competitive advantage • Opportunity to produce 25 million Mt/year of green hydrogen by 2050, generating exports worth more than $30 billion	https://www.energia.gob.cl/mini-sitio/hidrogeno-verde
China	China's Hydrogen Alliance (2018) Made in China 2025 (2015) Memorandum of Understanding CNOOC-Linde (2020)	• Foster the production of H_2: currently largest producer of grey hydrogen, from coal • Idea of launching a renewable energy hydrogen production • 2020-2030: over 1000 hydrogen refuelling stations; 1 million fuel cell vehicles • 2030-2050: hydrogen as an important component in energy mix • Invest in hydrogen production • Use of hydrogen in industrial applications, particularly mobility	http://www.ceic.com/gjnyjtwwEn/index.shtml https://www.linde.com/news-media/press-releases/2020
Denmark	Hydrogen Denmark	• Association that organises all stakeholders in the field of hydrogen and fuel cells • Pave the way for hydrogen and fuel cell technologies as the natural next step in the green transition	https://brintbranchen.dk/english/
European Union	EU Commission, hydrogen strategy for a climate-neutral Europe (2020)	• 2020-2024, the EU will support the installation of at least 6 gigawatts of renewable hydrogen electrolysers, and the production of up to one	https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

		million tonnes of renewable hydrogen • 2025-2030, hydrogen will become an intrinsic part of the integrated energy system, with at least 40 gigawatts of renewable hydrogen electrolysers and the production of up to ten million tonnes of renewable hydrogen • 2030-2050, renewable hydrogen technologies will reach maturity and be deployed at large scale across all hard-to-decarbonise sectors	
	European Clean Hydrogen Alliance (2020)	• Establish an investment agenda and support the scaling up of the hydrogen value chain across Europe • Estimated €430 billion investments until 2030	https://ec.europa.eu/growth/industry/policy/european-clean-hydrogen-alliance_en
	Hydrogen Europe	• European Hydrogen and Fuel Cell Association: represents 160+ industry companies, 83 research organizations, 21 National Associations • Partner with the EU Commission in the "Fuel Cells and Hydrogen Joint Undertaking" (FCH JU)	https://hydrogeneurope.eu/
France	Hydrogen National Strategy as part of the Recovery Plan (2020)	• € 3.4 billion by 2023 to fund a green hydrogen value chain - € 2 billion as part of Covid-19 recovery plan • € 7.2 billion by 2030 • Goal: ecological transition	https://www.economie.gouv.fr/files/files/directions_services/plan-de-relance/annexe-fiche-mesures.pdf
	Hydrogen Deployment Plan (2018)	• € 100 million to invest in hydrogen • 2023 and 2028 targets for low-carbon hydrogen	https://www.gouvernement.fr/en
	(Occitanie region, 2019)	• € 150 million to develop green hydrogen projects in 2019-2030 • Become leader in Europe for green hydrogen production	https://www.agence-adocc.com/wp-content/uploads/2019

Germany	National Hydrogen Strategy (2020) National Hydrogen Council (2020)	• € 9 billion to fund hydrogen infrastructure as part of Covid-19 recovery package • € 1,400 million over 10 years for the National Innovation Programme for Hydrogen and Fuel Cell Technologies	https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html
Hungary	New National Energy Strategy 2030 (2020)	• Develop a national hydrogen strategy • Importance of H_2 in the future energy mix • *Green* + *yellow hydrogen* (foster Hungarian nuclear capacity to produce H_2)	https://www.kormany.hu/en/ministry-for-innovation-and-technology https://www.kormany.hu/en/ministry-for-innovation-and-technology/news/
India	National plan on hydrogen R&D (2017)	• Support research and development on hydrogen and fuel cells	https://mnre.gov.in/img/documents
	Memorandum of Understanding India-Australia (2008)	• Task force for renewable energy cooperation on hydrogen/fuel cells • Facilitate R&D, trade, investments, industry-to-industry collaborations	https://mnre.gov.in/img/documents/uploads/46115f9a4b0547698c45187921df992c.pdf
	National Hydrogen Energy Roadmap (2006)	• Industry driven planning process, supported by Government and other stakeholders: based on Public-Private Partnership • Gradual introduction of hydrogen • Green Initiative for Future Transport	https://mnre.gov.in/
	Hydrogen Association of India	• Spearhead the promotion of hydrogen energy based programs on large scale	http://www.hai.org.in/index.html
	Indian Oil's hydrogen projects	• Hydrogen from biomass, methane reforming, electrolysis, and photolysis • R&D projects	https://iocl.com/AboutUs/environment(GFA).aspx
Italy	National Energy and Climate Plan (2020)	• Recognizes hydrogen's role in reducing CO_2 emissions • Public funds for R&D	https://www.mise.gov.it/index.php/it/energia/energia-e-clima-2030

	Hydrogen Table (2019)	• Launched by the Italian Ministry of Economic Development: public-private cooperation • Define priorities, guidelines, and make a competitiveness assessment on the Italian hydrogen sector • Promote the development of hydrogen-related projects	https://www.mise.gov.it/index.php/it/per-i-media/notizie/it/198-notizie-stampa/2039855-crippa-presiede-il-primo-tavolo-sull-idrogeno
	National Strategic Plan on Hydrogen Mobility (2016)	• Build the infrastructure for alternative fuels, of which hydrogen is a part	https://www.gazzettaufficiale.it/eli/id/2017/01/13/17G00005/sg
	Italian Hydrogen and Fuel Cells Association - H2IT (2005)	• Represents private companies and research centres • Public-private cooperation • Goal: develop a hydrogen infrastructure and a hydrogen market in Italy	https://www.h2it.it/
Japan	Basic Hydrogen Strategy (2017)	• Develop a hydrogen society • Reduce hydrogen costs to the same level of conventional energy	https://www.meti.go.jp/english/press/2017/1226_003.html
	New Strategic Roadmap for Hydrogen and Fuel Cells (2019)	• Targets and measures to foster the use of hydrogen	https://www.meti.go.jp/english/press/2019/0312_002.html
	Hydrogen included in the 2019-2020 budget, Ministry of Economy, Trade and Industry (2019)	• $150 million to establish a hydrogen supply chain • $ 91.7 million subsidies for public hydrogen station development	https://www.meti.go.jp/english/aboutmeti/policy/fy2019/0204.html
Netherlands	Government Strategy on Hydrogen (2020)	• Period up to and including 2021 will be used as the preparatory phase, with ongoing initiatives and projects to be used as a point of departure for a more comprehensive hydrogen national plan • Production can take place with the use of large electrolysers or production plants with CCS in the coastal regions	https://1fa05528-d4e5-4e84-97c1-ab5587d4aabf.filesusr.com/ugd/45185a_f22f45f329cf4841b7604f0c4e6d9c0b.pdf

	National Climate Agreement (2019)	• Targets for hydrogen production: 500 MW of installed electrolysis capacity by 2025 and 3 GW to 4 GW by 2030; and mobility: 15000 FCEVs, 3000 FC heavy-duty trucks and 50 HRSs by 2025, and 300000 FCEVs by 2030	https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/national-climate-agreement-the-netherlands
New Zealand	Green Hydrogen Strategy (2019)	• Low carbon hydrogen as an important component of the future energy mix: targets 2020-2025; 2025-2030; 2030 and beyond • Green hydrogen production, use and export	https://www.mbie.govt.nz/dmsdocument/6798-a-vision-for-hydrogen-in-new-zealand-green-paper
Norway	Norwegian government's hydrogen strategy (2020)	• Increase the amount of pilot- and demonstration projects by contributing to and supporting technology development and commercialisation • 120 million NOK to the ENERGIX-programme, in which hydrogen-related technologies and solutions have a central role	https://www.regjeringen.no/en/aktuelt/the-norwegian-hydrogen-strategy/id2704774/
Poland	Letter of intent to establish a partnership for building a hydrogen economy (Ministry of Climate, 2020) Private initiatives: PKN ORLEN set to build hydrogen hub in Włocławek (2020) PGNiG new hydrogen program (2020)	• Develop a Polish hydrogen strategy (to be published by end-2020) • Various methods of obtaining hydrogen (*not only green H_2*) • Collaboration between government and private companies • Produce 600 kg of purified hydrogen per hour • H_2 distributed primarily for use in public and freight transport • Build a green hydrogen production facility • H_2 for power generation and automotive applications • Hydra Tank project, experimental hydrogen refuelling station (2021)	https://www.gov.pl/web/climate/letter-of-intent-to-establish-a-partnership-for-building-a-hydrogen-economy-signed https://www.orlen.pl/EN/PressOffice/Pages http://en.pgnig.pl/news/-/news-list/id/pgnig-launches-new-hydrogen-program/newsGroupId/1910852
Portugal	National Strategy for Hydrogen	• Between € 7 and 9 billion of investments by 2030	https://www.portugal.gov.pt/pt/gc22/comunicacao/

	(2020)	• Development of a green hydrogen industry, which contributes to the reductions of natural gas imports	comunicado?i=estrategia-nacional-para-o-hidrogenio-aprovada-em-conselho-de-ministros
Russia	Draft action plan "Development of hydrogen energy in the Russian Federation" for 2020-2024 (2020)	• Opportunity to export low-carbon hydrogen, mainly to Europe • Pilot projects • Leading companies: Gazprom (tourquoise H_2); Rosatom (yellow H_2); NOVATEK (blue hydrogen)	https://www.tellerreport.com/business/2020
South Africa	Hydrogen South Africa – HySA, Hydrogen National Strategy (2008)	• Long-term (15-year) Hydrogen and Fuel Cell Technologies Research, Development, and Innovation strategy • Programmes: combined heat and power; Hydrogen Fuel Cells Vehicles	https://www.hysasystems.com/
Saudi Arabia	Agreement for the world's largest green hydrogen project - Air Products, ACWA Power, NEOM (2020)	• Onstream in 2025 • $5 billion for the production of green hydrogen-based ammonia production facility • Supply 650 tons per-day of green hydrogen	http://www.airproducts.com/Company/news-center/2020
South Korea	Hydrogen Law (2020) Roadmap to a hydrogen economy (2019) Plan to build 3 hydrogen-powered cities for 2022 (2019)	• Government support to hydrogen • H_2 safety standards for facilities • Leading the hydrogen vehicles and fuel cell industry • Establishing a system for hydrogen production and distribution. • Support the development of global standard technologies, and standardization efforts by the private sector • Hydrogen as the fuel for cooling, heating, electricity and transportation in Ansan, Ulsan and Jeonju/Wanju	http://www.law.go.kr/ http://english.moef.go.kr/pc/selectTbPressCenterDtl.do?boardCd=N0001&seq=4654 http://www.korea.net/Government/Briefing-Room https://www.weforum.org/agenda/2019
Spain	Public consultation over a National Hydrogen Roadmap (2020)	• Rollout of at least 4 GW of electrolysis capacity by 2030, along with a 25% share for green hydrogen in industrial	https://energia.gob.es/en-us/Participacion/Paginas/DetalleParticipacionPublica.aspx?k=337

		processes	
United Kingdom	Hydrogen Advisory Council (2020) Hydrogen Projects (2020)	• Unlock low-carbon hydrogen potential in the 2020s • Collaboration between government and industry • £28 million funds for low-carbon H_2 projects, including 2 plants	https://www.gov.uk/government/groups/hydrogen https://www.gov.uk/government/news
United States	Hydrogen and Fuel Cells Program H2@Scale Initiative (2016) "Private" Hydrogen Roadmap California Hydrogen Vehicles and Refueling Infrastructure Program California Hydrogen Business Council	• Conduct research and development on hydrogen • Explore the potential for a hydrogen energy future • Efficiently scale-up the production of hydrogen using all of United States' energy sources • In 2020 $64 million funding for 18 projects to support hydrogen production, storage, distribution, and use. • A coalition of major oil & gas, power, automotive, fuel cell, and hydrogen companies developed a Road Map to a US Hydrogen Economy • Develop FCEV and a hydrogen fuelling market • Initial network of 100 public hydrogen stations across California • Target: 200 stations by 2025 • Comprised of 100+ companies and agencies involved in the business of hydrogen, common goal of advancing the commercialization of hydrogen • Reinforce California's position as the most advanced clean energy state in the US	https://www.hydrogen.energy.gov/index.html https://www.energy.gov/eere/fuelcells/h2scale http://www.fchea.org/us-hydrogen-study https://ww2.arb.ca.gov/our-work https://www.energy.ca.gov https://www.californiahydrogen.org/

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Fondazione Eni Enrico Mattei
Corso Magenta 63, Milano – Italia

Tel. +39 02.520.36934
Fax. +39.02.520.36946

E-mail: letter@feem.it
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